UAH
The University of Alabama in Huntsville

Research Administration

Huntsville, Alabama 35899
Phone: (205) 890-6000
Fax: (205) 890-6677

June 15, 1998

U.S. Army Aviation & Missile Command
AMSAM-RD-SE-PE
Attn: Mr. Dan Holder
Redstone Arsenal, AL 35898

RE: Final Report
DAAH01-92-D-R006 D.O. 110

Dear Mr. Holder:

Please find enclosed one copy of the above noted **Final Report** for "Design Tools for Assessing Manufacturing Environmental Impact" as required by the above referenced contract.

If you have any questions or need additional information, please contact me at (256) 890-6000 ext. 224.

Sincerely,

Kimberly R. Horvath

Kimberly R. Horvath
Contract Assistant

ENC.

cc:	AMSAM-AC-RD-BB Bldg 5400 Rm B148/Judy Sutherland	(ltr/rpt)
	ONRRO	(ltr/rpt)
	DTIC/OCA	(ltr/2 rpt)
	UAH/Dr. Sherri L. Messimer	(ltr)
	UAH/Dr. Damiel M. Rochowiak	(ltr)
	UAH/ Accounting	(ltr)
	UAH/File	(ltr/rpt)
	UAH/Archives	(rpt)

PLEASE CHECK THE APPROPRIATE BLOCK BELOW

DAO# ___________

☐ ___________ copies are being forwarded. Indicate whether Statement A, B, C, D, E, F, or X applies.

☒ DISTRIBUTION STATEMENT A:
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED

☐ DISTRIBUTION STATEMENT B:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES ONLY; (indicate Reason and Date). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT C:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND THEIR CONTRACTS (Indicate Reason and Date). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT D:
DISTRIBUTION AUTHORIZED TO DoD AND U.S. DoD CONTRACTORS ONLY; (Indicate Reason and Date). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT E:
DISTRIBUTION AUTHORIZED TO DoD COMPONENTS ONLY; (Indicate Reason and Date). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT F:
FUTHER DISSEMINATION ONLY AS DIRECTED BY (Indicate Controlling DoD Office and Date) or HIGHER DoD AUTHORITY.

☐ DISTRIBUTION STATEMENT X:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND PRIVATE INDIVIDUALS OR ENTERPRISES ELIGIBLE TO OBTAIN EXPORT-CONTROLLED TECHNICAL DATA IN ACCORDANCE WITH DoD DIRECTIVE 5230.25. WITHHOLDING OF UNCLASSIFIED TECHNICAL DATA FROM PUBLIC DISCLOSURE, 6 Nov 1984 (indicate date of determination). CONTROLLING DoD OFFICE IS (Indicate Controlling DoD Office).

☐ This document was previously forwarded to DTIC on ___________ (date) and the AD number is ___________.

☐ In accordance with provisions of DoD instructions. The document requested is not supplied because:

☐ It will be published at a later date. (Enter approximate date, if known).

☐ Other. (Give Reason)

DoD Directive 5230.24, "Distribution Statements on Technical Documents," 18 Mar 87, contains seven distribution statements, as described briefly above. Technical Documents must be assigned distribution statements.

Sherri L. Messimer
Print or Type Name

Sherri L. Messimer 6/15/98
Authorized Signature/Date

(256)890-6211
Telephone Number

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution Statement A
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UAH	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION UAH — 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 301 Sparkman Dr Huntsville AL 35899	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION ARMY — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Design Tools for Assesing Manufacturing Environmental Impact

12. PERSONAL AUTHOR(S)
S. Messimer, D. Rochowiak, P. Farrington, B. Rogers, M. Bower, C. Karr

13a. TYPE OF REPORT Final	13b. TIME COVERED FROM ____ TO ____	14. DATE OF REPORT (Year, Month, Day) Nov 26 1997	15. PAGE COUNT 121 (est.)

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A final report on a simulation and software development project focused on the environmental impact of composite material manufacturing.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) — 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 — Previous editions are obsolete. — SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

Design Tools for Assessing Manufacturing Environmental Impact

5. FUNDING NUMBERS

6. AUTHOR(S)

S. Messimer, D. Rochowiak, P. Farrington, J. Rogers, M. Bower, C Kao

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

Distribution Statement A

13. ABSTRACT *(Maximum 200 words)*

A final report on a simulation and software development project focused on the environmental impact of composite material manufacturing

14. SUBJECT TERMS

15. NUMBER IF PAGES

1

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Design Tools for Assessing Manufacturing Environmental Impact

Final Report

Contract No: DAAH01-92-D-R006

Delivery Order: 110

prepared by:

Sherri Messimer

Dan Rochowiak

Phillip Farrington

John Rogers

Mark Bower

at

The University of Alabama in Huntsville

and

Charles Karr

The University of Alabama

November 26, 1997

Table of Contents

Table of Appendices

DTAME - Final Report

1.0 Introduction

As the DoD undergoes a reshaping and resizing to achieve a more affordable defense capability, it is also important that weapon systems be developed and manufactured in an environmentally conscious manner. To achieve this goal requires that a change occur in the paradigm that is used to view the weapon system life cycle. In today's paradigm, the addressing of environmental concerns occur as a defacto activity after the product, process, and manufacturing plan have been established. Many studies have shown that this reactive approach is not effective. Currently, the DoD and its contractors are in the process of "cleaning up" their facilities and weapon system designs due to inadequate environmental planning.

Proposed actions to effect a more environmentally conscious approach must be enacted early in the life cycle phase to achieve optimal facility and weapon system designs. This paradigm change requires that we view environmental concerns as an important factor in the trade-off decision making that must occur during the early development phases. Assessing pollution impacts and energy consumption during the early phases of product development will result in long term savings and a significant reduction pollution (i.e. hazardous waste generation). The impacts of environmental laws and regulations must be assessed during the earliest design phases of product development in order to affect changes in the product, process, or manufacturing plan.

Assessing pollution impacts and energy consumption during the early phases of product development results in long term savings and a reduction in pollution. Tools are needed which allow designers to understand the consequences of their decisions regarding manufacturing options. We believe that to attack this problem we will need to intelligently access and integrate information and regulations from diverse sources in a way that is both timely and meaningful to the end user. Identifying the environmental impact during the early planning stages allows the manufacturer to reduce the impact early when changes in the production system are easily made.

Currently, Program Management Office personnel do not have the expertise to address the environmental impacts of design decisions made during the design process. The Design Tool for Assessing Manufacturing Environmental Impact (DTAME) allows the design engineers, concurrent engineering teams, and Program Managers to understand the environmental consequences of their decisions regarding manufacturing process options early enough in the program life-cycle to affect positive actions.

DTAME builds on capabilities and systems developed in two previous research projects: a system used to critique the applicability of a particular composite manufacturing process and an interactive simulator developed to rapidly define, model, and evaluate electronic manufacturing systems. We also utilize results from the Army's fuzzy logic controller for helicopter flight control as part of a search strategy involving genetic algorithms to optimize system configuration.

1.1 Composite Materials

Composites are a class of materials that are formed from two or more macroscopically combined constituents. These materials derive their properties from some combination of the properties of the constituents to yield desirable properties different from that of the constituents. We will limit our discussion to processing methods for reinforced plastics. These typically combine a thermosetting or thermoplastic matrix with a fibrous reinforcement that has a relatively high strength and modulus.

The basic steps for fabricating composite material parts are: begin with the plastic matrix and reinforcement, co-mingle the matrix and reinforcement, form the co-mingled composite into the part geometry, cure or heat the composite, and finally perform any required finishing or joining operations. Curing applies to thermosetting plastics and is a chemical and physical change of the plastic from a liquid to a solid. Thermoplastics do not cure but undergo a phase transformation when heated to form the plastic into a given form or geometry.

While typical finished composite parts are chemically benign and pose little ecological threat, environmental concerns and issues arise in the basic composite manufacturing steps. Based on our research with the Composite Design Manufacturing Critiquing System (CDMCS), we found that there is a significant impact by several environmental regulatory acts on composite material manufacture which establish what materials constitute hazardous waste, regulate treatment and disposal, and establish reporting requirements for chemical release, waste reduction, recycling and energy recovery. Ignorance of these regulations could result in severe penalties. Consequently, composite manufacturers are sensitive to these regulatory acts and must keep abreast of updates and revisions.

1.2 History

The Design Tool for Assessing Manufacturing Environmental Impact (DTAME) builds on capabilities and systems developed in two previous research projects: a system used to critique the applicability of a particular composite manufacturing process and an interactive simulator developed to rapidly define, model, and evaluate electronic manufacturing systems. We also utilize results from the Army's fuzzy logic controller for helicopter flight control as part of a search strategy involving genetic algorithms to optimize system configuration.

1.2.1 Background and Motivation: Simulation Tools

Whether maintaining and improving existing production lines or designing new lines, simulations are employed to evaluate and compare alternatives. Simulation is often the only viable choice for analysis of complex manufacturing systems especially where there is a high degree of interdependence between design, process equipment, and process control. Simulation provides an effective tool for evaluating system configurations and new processing strategies. If properly constructed and maintained, a simulation model of an existing production line can be used to:

- evaluate the impact of product mix changes,

- evaluate the impact an individual station's speed and reliability on overall system performance,
- compare the system throughput and capacity with different process configurations,
- provide environmental data that could be integrated with process cost information to develop more detailed and accurate models of processing, and
- compare the performance of the different system configurations required for competing design technologies.

Tools for simulating for manufacturing systems have developed greatly in the last decade. However, these tools have not directly addressed the issues of simulation definition in the context of environmental concerns and multiple metrics for performance. Simulation tools do not provide cost modeling or optimization routines, either. The typical tool concentrates on providing throughput and capacity information for assessing the impact of product mix changes or an individual station's speed and reliability on overall system performance.

1.2.2 Previous Projects

DTAME builds upon our previous research efforts with interactive graphical and interactive iconic simulations and the Helicopter Flight Control With Fuzzy Logic and Genetic Algorithms project with the Army and the U.S. Bureau of Mines. A description of the CDMCS system is provided below, followed by a description of the SEEM system. We will also provide a brief description of the approach used in the helicopter controller project.

CDMCS: Composite Design and Manufacturing Critiquing System

CDMCS assists a design engineer by critiquing proposed manufacturing methods of composite parts. The critique provided by CDMCS is built by comparing the design parameters for a specified part against a set of design rules and parametric relationships which govern the acceptability of individual composite part manufacturing processes. The rules and metrics that qualitatively simulate an expert's knowledge are divided into three categories: requisite metrics, core metrics and enabling metrics. Requisite metrics are Boolean and must be satisfied. Core metrics must be satisfied to a high degree. Finally, enabling metrics are those

metrics that are not vital to the acceptability of a candidate process, but enhance or detract from its desirability.

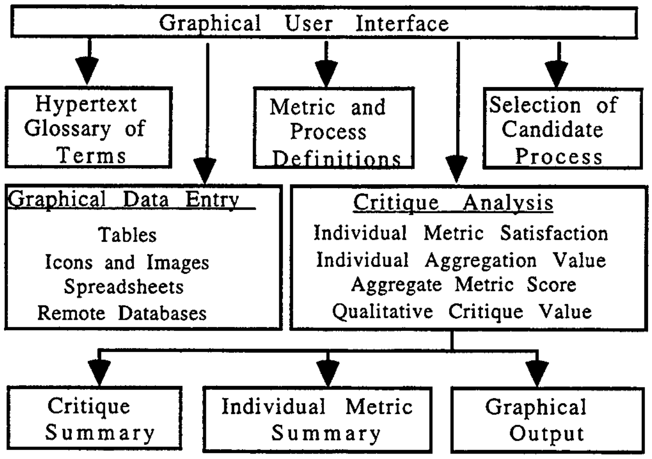


Figure 1.1

Figure 1.1 illustrates the general architecture of the CDMCS. A graphical user interface allows the user to operate the system and observe results. Help facilities are provide to assist the user in terminology and metric definitions. Network links connect the system to remote databases which allow for the most current selections of materials and other parameter values. Previous design cases are stored with relative success values and the user can compare her or his design against the case library. When the critique is complete the user can add the case to the library. Thus, the case library acts as an ever increasing manufacturing memory. An aggregate score for the candidate process is obtained by analyzing each of the metrics that apply to a specified candidate process. The success values for the metrics are aggregated into an overall score. The aggregation function maintains acceptability requirements and promotes high success for various metrics. The aggregate score for the process is then mapped to a qualitative rating from very poor to highly acceptable. The qualitative rating is used to produce both explanatory text and graphical representations. The system also provides suggestions for improving the aggregate score.

Interactive Iconic Simulation: SEEM

Simulation Environment for Electronics Manufacturers (SEEM) is being developed to rapidly define, model, and evaluate electronics manufacturing systems. The major components of the system are the problem definition, static analysis, and code generation modules (Figure 1.2). Each module provides feedback to the other modules and reports to the user. While the domain knowledge in SEEM is specific to electronics manufacturing, its architecture is general enough to be used for other domains with appropriate domain information and knowledge.

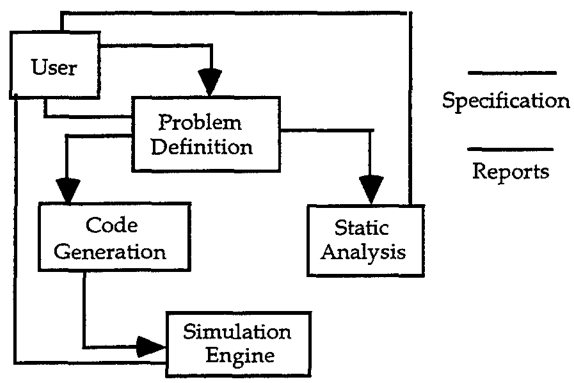


Figure 1.2

The initial definition of an electronics assembly system is built by the user through the problem definition module's graphical user interface. Icons which represent the various equipment elements can be placed anywhere in a two-dimensional graphical workspace. The user enters the definitions for line entry, line exit, assembly stations, buffers, inspection stations, ovens, conveyors, line divergence points, line convergence points, and other related items. The static analysis module uses the component processing times for each component to generate a maximum throughput for each component of the line for a specified period and identifies bottlenecks for both non-branching and branching models. For both the problem definition and the static analysis the user receives reports from the system that allow her or him to respond to various problems and difficulties before committing to a simulation model. Once the user is satisfied with the model, simulation language code is generated and executed. The reports from

the code and simulation engine are sent to the user, and the process can iterate until satisfactory results are produced.

SEEM supports rapid prototyping and concurrent engineering by creating a virtual manufacturing environment that improves the clarity of the model, increases productivity, reduces the modeler's need to know the details of a simulation language, and provides for easier maintenance and improved documentation.

Helicopter Flight Control

Researchers at the U.S. Bureau of Mines and the U.S. Army have developed a fuzzy logic controller for manipulating UH-1 helicopters. Since this is an extremely difficult task, the resulting controller was quite complex. In fact, control tasks are partitioned into four individual units, each of which has its own rules and associated membership functions. Because of the large number of rules, and because the rules were not necessarily like those a human pilot would use, an efficient technique for writing the rules was required. A genetic algorithm was used for this task as they have demonstrated the ability to generate fuzzy logic controller rules. Genetic algorithms are search algorithms based on the mechanics of natural genetics.

2.0 Domain Description

A composite material is a combination of two or more distinct materials, differing in form or composition on a macroscale; that is, a heterogeneous solid where the components maintain their characteristic structure and properties. Composites are often chosen when weight savings are critical, and when one homogeneous material cannot meet the design requirements. There are many forms of composite materials and several methods of classification. One method of classification divides composite types into three categories: laminar (such as plywood), particulate (such as concrete), and fiber-reinforced (such as automobile tires). Fiber-reinforced composites are the most prevalent type of composite material for engineering applications, and are the focus of this research. These composites are formed from reinforcing elements, fillers, and a matrix phase. A composite material possesses a unique combination of characteristics, such as stiffness, strength, and weight, that depend on the materials used as the binder, the volume fraction of reinforcing elements contained in the matrix, and the orientation of these reinforcing elements.

2.1 Composite Materials and Design

Matrix phase materials are often some type of polymer, although metal and ceramic matrix composites are emerging as leaders for high operating temperature applications. Only polymer based composites, such as epoxy resins, are being considered in the current implementation of DTAME. Common reinforcing materials for these polymer composites include glass, boron, aramid, graphite, and carbon fibers. Common reinforcing materials for these polymer composites include glass, boron, aramid, graphite, and carbon fibers. Innovative uses of polymer based composites can be found in sporting and recreation equipment such as golf clubs and tennis rackets (epoxy matrix/graphite fibers), boats (polyester/glass fibers), fishing rods (epoxy/carbon and glass fibers). Polymer based composites have also found successful application in space and missile systems, and aircraft components as was evidenced in the Voyager aircraft, of which nearly 90% is made from graphite fibers.

Design engineers, equipped with sketchy information at best, have attempted to apply sequential design methods in which a material is chosen for its properties, followed by a choice for a manufacturing process. However, composite materials exhibit a high degree of coupling among many of the most important decisions such as materials and manufacturing process. Composites manufacturing is a materials transformation process composed of a sequence of stages, as illustrated in Figure 2.1 below. The process may include most, if not all, of the stages shown below. Decisions made concerning the manufacturing process must take into account matrix material, fiber reinforcement, and fiber volume. The selection of raw material, the configuration of this raw material, and the choice of a primary processing method are tightly coupled decisions impacting the producibility of the part.

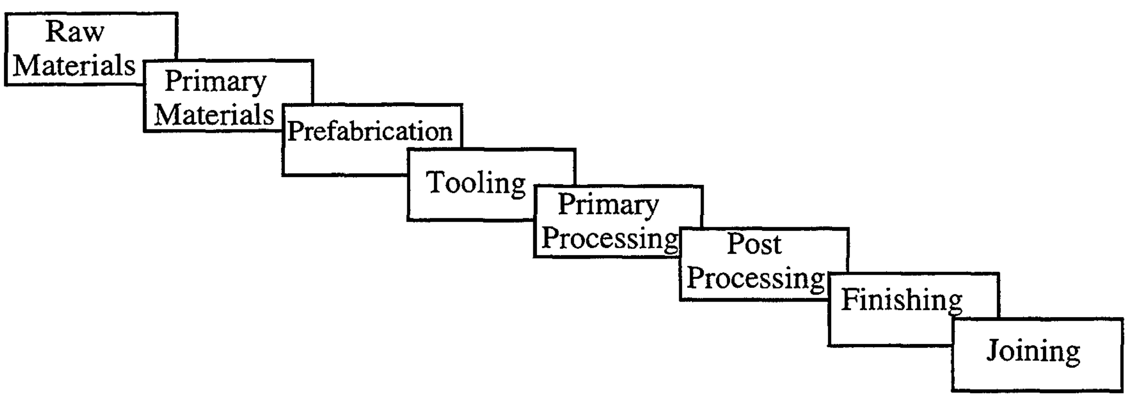


Figure 2.1 Composite Manufacturing Stages

A complete processing plan for composite materials entails specifying the following:

Raw Materials + Primary Materials + Prefabrication + Tooling + Primary Processing + Post Processing (curing) + Finishing + Joining

There are a finite number of options for each of these eight stages in the composites manufacturing process. Making selections in one stage is usually not independent of selections in the other stages. Thus, it makes little sense to start with the "first" stage, Raw Materials, make a selection, and then go on to the second, etc. We have found that the Primary Processing, Primary Materials, and Tooling stages are often the most important stages to be considered. That is, these three stages may often be specified before, and nearly independently of, the other stages. While this is not always true, it is taken as an assumption for this work.

2.2 Composite Manufacturing

A number of primary processes are used to produce composite materials. Figure 2.2 shows the classification of manufacturing processes for fiber reinforced polymer composites. These are the core manufacturing processes; there are numerous variations of each of these processes. In general, the manufacturing options available can be identified based on the type or shape of product being produced. After the field is narrowed, process design criteria can be used to determine which manufacturing process would be the best alternative.

Two primary processes are discussed in this report. The first, Filament Winding, serves as the prototype process to illustrate the DTAME methodology. The second, the Vacuum Assisted Resin Transfer Molding (VARTM) process is a variation of the Resin Transfer Molding process.

2.2.1 Filament Winding

The methodology developed in this research is applied to the development of reusable models of the filament winding process. Figure 2.3 shows a block diagram of the filament winding operation. The filament winding process begins with the preparation of the mandrel for operation. Both a fixed or one use mandrel can be used; however, both require reusable mandrel

apparatus that must be removed after curing. If a fixed mandrel is used it must be treated with mold release or have some type of liner applied. One use mandrels are usually made of foam, sand, or plaster. Once the mandrel is prepared the actual winding operation is initiated. Figure 2.4 shows a general diagram of a common filament winding operation. Filament winding is a process in which resin impregnated continuous fibers are wrapped around a rotating mandrel that has the internal shape of the desired product. There are three methods by which the fibers can be impregnated with resin:

1) Wet winding - filament is pulled through a resin bath prior to winding.
2) Prepreg or dry winding - filaments preimpregnated with partially cured resin are wrapped around a heated mandrel.
3) Postimpregnation - filaments are impregnated with resin after being wound onto a mandrel.

The first two methods are by far the most popular. The two main types of winding patterns employed with filament winding, helical and polar, are shown in Figure 2.5. The next step is the curing process. This generally takes place out in the open, in an oven, or in an autoclave. Once the part is cured the mandrel apparatus is removed. Any finishing of the part such as cutting or sanding is generally done after mandrel removal and prior to final inspection.

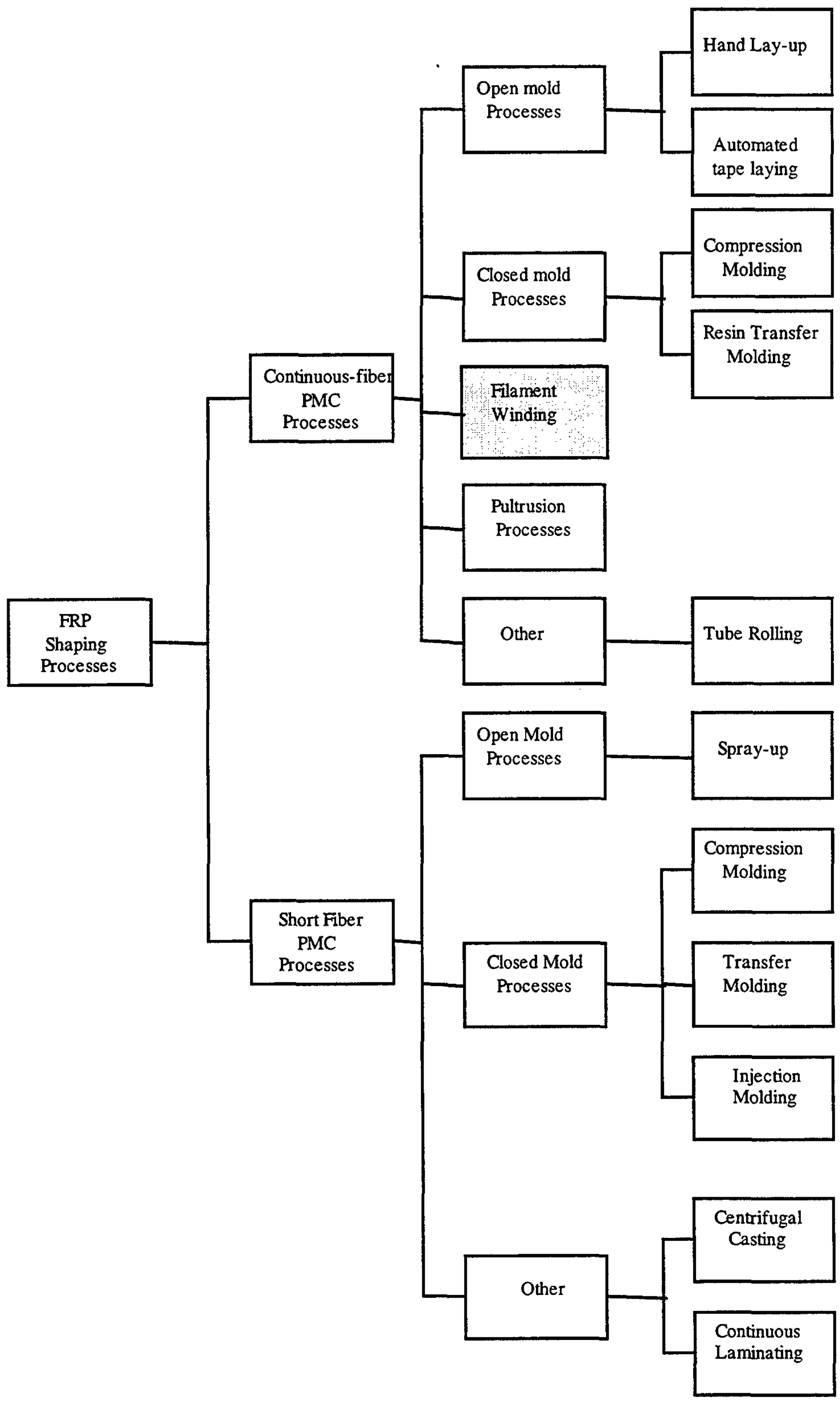


Figure 2.2 Classification of Manufacturing Processes for Fiber-Reinforced Polymer Composites [Groover, 1996]

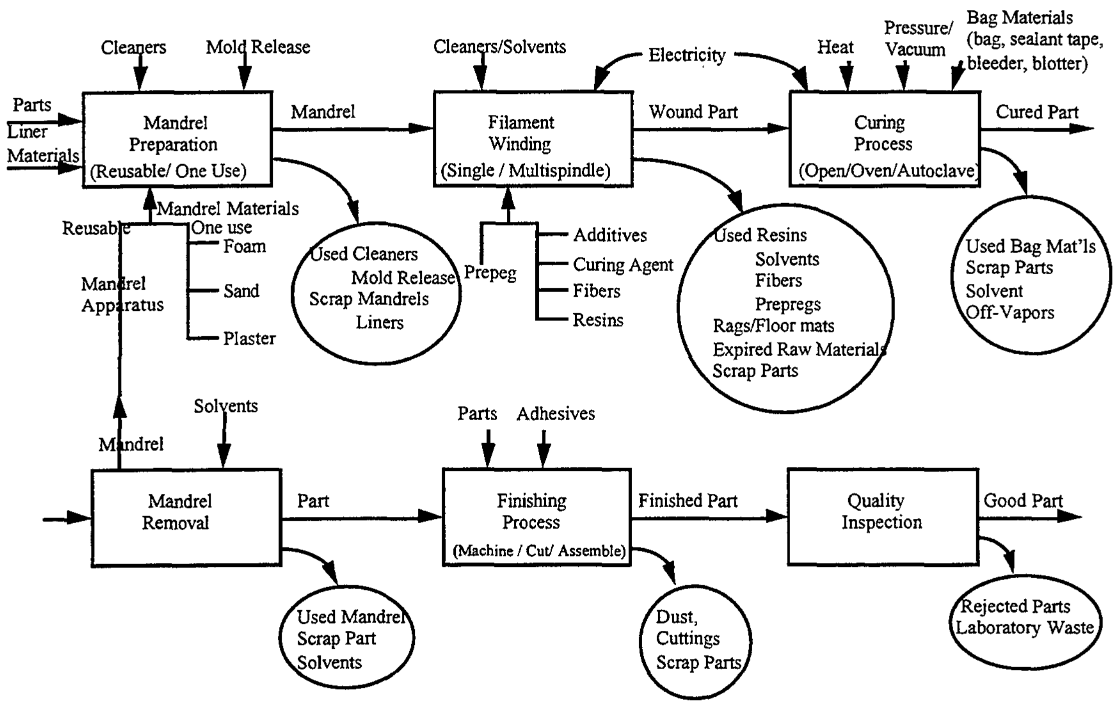


Figure 2.3 Filament Winding Flowchart

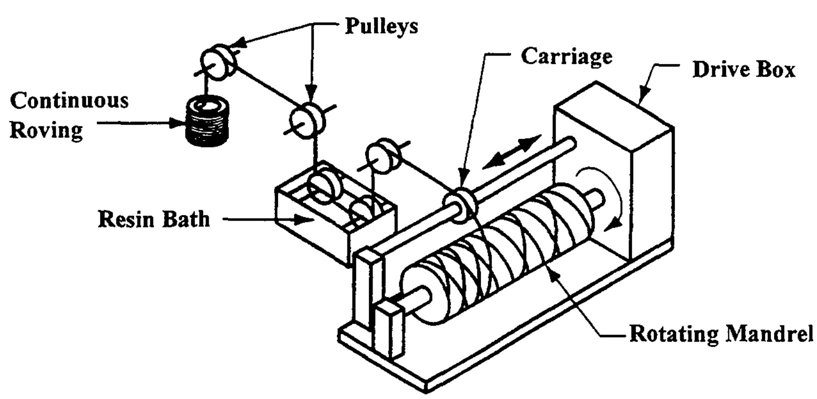


Figure 2.4 Filament Winding Operation [Groover, 1996]

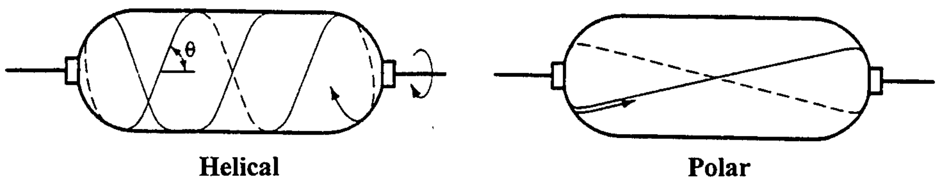


Figure 2.5 Winding Patterns [Groover, 1996]

Products produced using the filament winding process include rocket-motor cases, helicopter blades, piping, tubing, and drive shafts. Figure 2.6 shows a partial list of the numerous requirements and parameters an engineer would consider when designing a filament winding process.

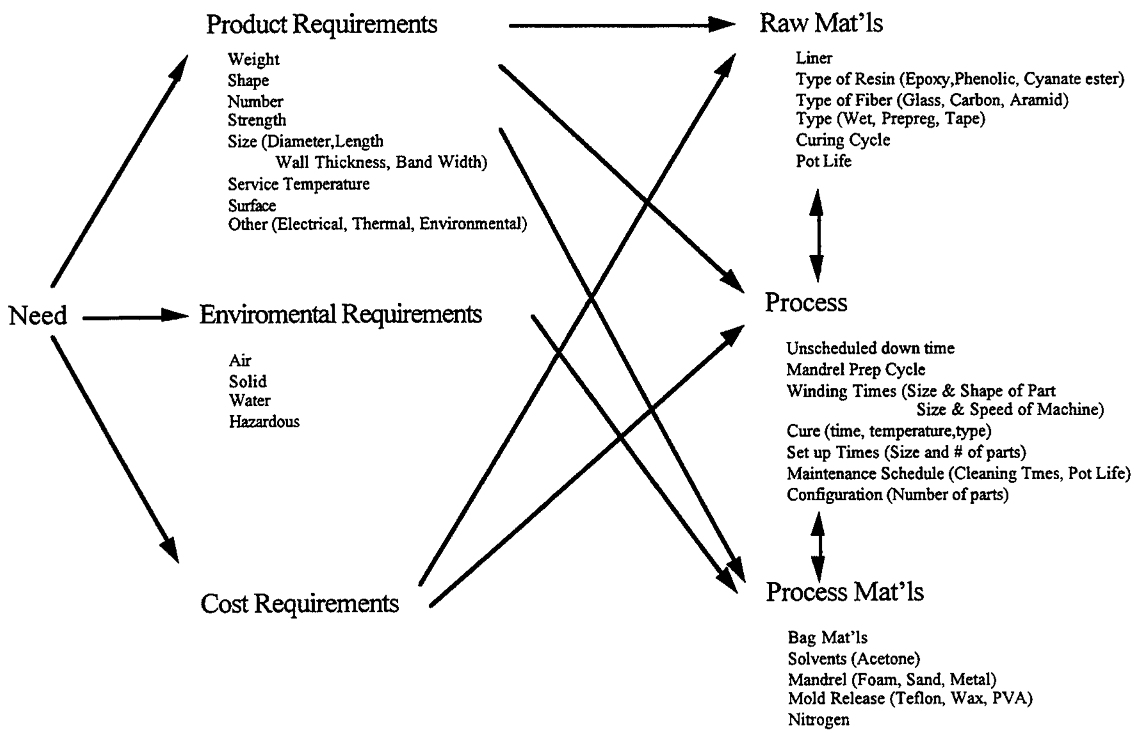


Figure 2.6 Parameter Diagram for Filament Winding

2.2.2 Vacuum Assisted Resin Transfer Molding (VARTM)

VARTM or Vacuum Assisted Resin Transfer Molding is used for fabricating composite parts. It consists of eight main process steps which are shown in the diagram below. During the first step a mold is prepared by cleaning and applying a mold release agent to it. The prepared mold is then sent to the lay-up step where a fiber based lay-up material is placed in the mold. A number of lay-up operations can be done consecutively depending on the complexity of the part. The mold is closed and placed in a vacuum bag in preparation for the resin infusion step. During the resin infusion step resin is transferred into the mold cavity by pulling a moderate vacuum. The part is then staged or cured and the bag and mold are removed. The part is sent to any finishing operations that still need to be performed. During the last step the part is inspected. As can be seen in the diagram the five steps including lay-up, VARTM set-up, resin infusion, stage/cure, and bag/mold removal can be repeated if necessary.

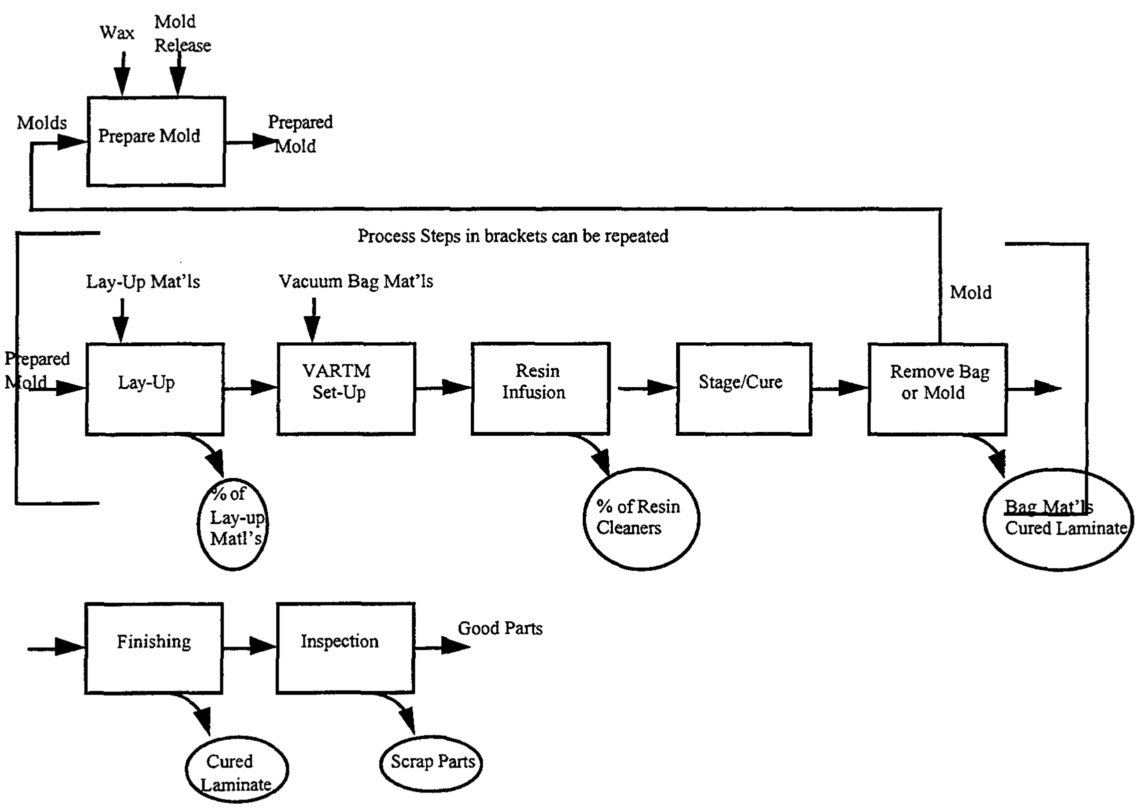


Figure 2.7 VARTM Flow Diagram

2.3 Composites and Environmental Issues

In order to effectively design a model which takes into account environmental criteria it is important to understand how environmental issues affect the composite industry. Therefore, Table 21 lists and describes the five major pieces of legislation which affect all manufacturers.

Table 2.1 Environmental Legislation [Fisher and Witzler, 1992]

Name	Description
The Resource Conservation and Recovery Act (RCRA)	Defines both solid and hazardous wastes and regulates the treatment and disposal of each.
The Toxic Substances Control Act of 1976 (TSCA)	Regulates chemicals to be imported, created, or used in any manufacturing process. Waste management is included.
The Emergency Planning and Community Right-to-know Act (EPCRA)	Requires annual reports of environmental releases of about 300 chemicals and information on efforts to reduce waste, recycle, and recover energy.
Clean Air Act	Mandates the EPA to regulate air emissions, including listed air toxins.
Clean Water Act	Mandates the EPA to establish and revise standards for industrial discharges to surface waters and public treatment facilities.

How does this legislation specifically affect the composite industry? Fortunately, very few substances used in advanced composites are currently considered hazardous. However, hazardous wastes generated at composite manufacturing facilities generally include solvents and prepregs or resins containing solvents. In addition, personal protective equipment, liners, and bagging materials used in the curing process may also require hazardous waste disposal.

In compliance with the Clean Air Act, companies are required to register air-emission sources such as ovens and autoclaves and obtain prior approval for all new emission sources. Other possible sources of air emissions include mold-release agents, cleaning agents, and other volatile solvents. Many companies also have to place emission controls on their finishing and prepregging operations.

Solid waste is another area for concern in composite manufacturing. Composite materials including prepreg waste is one of the solid waste disposal problems. There are many complex definitions and requirements when dealing with solid waste. Most often any uncured resin is

allowed to cure and is labeled as non-hazardous waste. Companies prefer this approach since hazardous waste is about 10 times as expensive to dispose of as nonhazardous waste. In some instances, however, companies which cure prepreg as a method of treating hazardous waste may have to hold a permit as a treatment, storage, and disposal facility. Since obtaining a permit is a very costly procedure, many smaller companies may be forced into hazardous waste disposal.

Even though many wastes in the composite industry are not considered hazardous at this time, larger companies may still treat them as hazardous because of their uncertain long term outlook. Materials, currently not on the RCRA list of hazardous materials, may eventually gain that status and there are no "grandfather" clauses in hazardous waste legislation. Ten to twenty years in the future companies do not want expensive clean-up costs putting them out of business. Also, the Occupational Safety & Health Administrations (OSHA) Hazard Communication Standard requires a Material Safety Data Sheet (MSDS), which outlines the important safety and environmental information associated with a product, for all materials deemed hazardous to workers.

Environmental regulations are important to consider when addressing environmental criteria; however, overall waste minimization is important as well. It is estimated that for aerospace applications the industry purchases two pounds of raw materials for every pound in the final composite product. One study authorized by the Center of Excellence for Composites Manufacturing Technology estimated that 2.5 million pounds of prepreg waste are disposed of annually which is equivalent to $1 billion in prepreg and prepreg by-products. Another $25 million is spent on waste disposal [Fisher and Witzler, 1992]. The Guide to Pollution Prevention for the Fiberglass-reinforced and Composite Plastic Industry lists the most common types of waste, origin, and composition as shown in Table 2.2. In the guide there are also a number of waste minimization methods that are given for particular waste streams as summarized in Table 2.3.

Table 2.2 Fiberglass-Reinforced and Composite Plastics Fabrication Waste [EPA,1991]

Waste Description	Process Origin	Composition
Waste solvent	Hands, tool mold, and equipment cleaning	Resin-contaminated solvent
Empty resin and solvent containers	Unloading of materials into mixing tanks	Small amounts of residual resin and solvent
Laboratory analysis wastes	Formulating and testing	Spent resins, solvents, and finished and semi-finished trial products
Cleanup rags	Equipment cleaning operations	Solvents and small amount of resins
Pre-preg (previously resin-impregnated) waste fabric	Leftovers from a particular batch or scrapped when product sample does not meet customer specification	Resins and fiberglass substrate (including minor quantities of chemical additives)
Empty plastic, paper and cardboard containers with residual peroxides, glass routing and chemical additives	Unloading of raw materials into process tanks	Chemical additives such as "Cab-O-Sil" and aluminum trihydrate
Expired raw materials	Raw material that has exceeded shelf life or otherwise became unusable	Usually semi-solid and self-cured resin
Gelcoat and resin overspray	Overspray during fabrication process	Resins, pigments, catalysts and chemical additives
Scrap solvated resin	Residue from piping and treated pan at the end of a run	Resins and resin-contaminated solvents
Partially-cured waste resins	Discontinued batch	Contaminated and unusable resin solvents
Volatile organic compounds	Volatilized solvent and mold release agents, during curing and open vessels containing solvents	Solvents and volatile monomers
Waste water	Equipment cleaning with emulsifiers	Water with organic chemical contaminants and emulsifier

Table 2.3 Waste Minimization Methods for Fiberglass Reinforced and Composite Plastics Fabricators [EPA, 1991]

Waste Stream	Waste Minimization Methods
Equipment cleaning wastes	Restrict solvent issue. Maximize production runs. Store and reuse cleaning wastes. Use less toxic and volatile solvent substitutes. On-site recovery. Off-site recovery. Reduce rinse solvent usage. Waste segregation.
Scrap solvated and partially cured resins	Modify resin pan geometry. Reduce transfer pipe size. Waste exchange.
Gelcoat resin and solvent oversprays	Change spray design.
Rejected and/or excess raw material	Improve inventory control. Purchase materials in smaller containers. Return unused materials to suppliers.
Resin and solvent contaminated floor sweepings	Use recyclable floor sweeping compound. Reduce solvent and resin spillage and oversprays by employing alternate material application and fabrication techniques.
Empty bags and drums	Cardboard recovery. Container recycling. returnable containers. Use plastic liners in drums.
Air emissions	Improve/modify material application. Cover solvent containers. Use emulsions or less volatile solvents.
Miscellaneous waste stream	Product/process substitution.
Cleanup rags	Efficient utilization of clean programs. Auto-cleaning process equipment.
Laboratory and research wastes	Reduce quantities of raw material and products for testing and analysis.

With the increasing concern about environmental impacts and the upcoming implementation of ISO-14000 environmental systems standards, companies will be looking for more cost effective methods to include environmental criteria into the design process. A simulation model which uses inventory analysis to track materials entering and leaving the manufacturing process could greatly enhance a design engineers ability to assess environmental performance before selecting and installing a manufacturing process. The composite industry, because of its many different manufacturing alternatives and its strong need for concurrent engineering, is a good choice to show the viability of this methodology.

3.0 Problem Overview

In the design and manufacture of parts using composite materials there is a strong distribution of knowledge and information. The distribution of knowledge is strong in the sense that at both the macro and micro scales there is little in the way of stable, coordinated, and accessible resources. In part this is due to the rapid evolution of the field, in part it is due to the proprietary nature of the materials (resins, fibers), in part it is due to the proprietary nature of the machines and production processes, and in part it is due to the need for the expert's art. There are also many other factors. Some of these include that need for a transition from traditional materials and manufacturing techniques to the new techniques, the geographical dispersion of experts, the industrial dispersion of expertise, and the lack of a critical mass of composite material designers and manufacturers.

The distribution of knowledge and information presents a challenge for those that intend to adopt composite material technologies. The current regime of design and manufacturing engineers may not have the requisite knowledge of the field and may find it very difficult to get the materials through which they could gain this mastery. Further, the use of composite materials may pose new challenges for life-cycle planning and environmental analysis. While some of these issues have been studied for the traditional materials of design and manufacture, they newness of composite materials technologies have made such studies difficult in this area.

The problem is that there is desire to use composite materials in design and manufacture, but there are no near-to-hand knowledge sources for the domain. Further these knowledge sources would need to cross fields of expertise and need to be updated frequently. How then can system be constructed for composite materials design and manufacture that addresses:

The evolution of composite materials
The evolution of manufacturing techniques
The distribution of expertise
The need for expertise in multiple domains?

4.0 Problem Definition

4.1 Emerging Technologies

Composite materials are the result of the marriage of two or more materials on a macroscopic scale to produce a single heterogeneous material displaying, at least in the ideal, the best properties of the individual constituents. The variety in composite materials is incredibly broad due to the wide range of materials that can be combined as a composite material along with the range in amounts of matrix (typically resin) and suspension (typically fiber), and the order, form, and method of combination. The importance of the constituents of a composite material cannot be overstated. Ultimately every property of a composite material is dependent on the properties of the constituent materials. Therefore, improvements in the performance of a composite material can be achieved through improvements in the constituents. Not withstanding the importance of the constituents, significant improvements in the performance of a system involving composite materials can be achieved through improvements of the composite manufacturing process. Due to the integrated nature of a composite material it is not uncommon for a design to fail to take full advantage of the properties of the composite material.

Advances in composite materials are occurring seemingly on a daily basis. These advances are taking place simultaneously on multiple fronts. Developments are coming in the resin systems, in the fiber systems, and in the manufacturing processes for the composite. Improvements to resin systems are producing systems with enhancements in one or more of the following characteristics: high temperature properties, toughness, stiffness, processing time, processing cost, or production methods. Improvements in fiber systems are yielding fibers enhancements in one or more of the following characteristics: stiffness, strength, toughness, high temperature properties, matrix bond quality, and processing cost. Advancements in production methods for the composite systems are equally productive, leading to composite parts that have greatly improved performance with lower manufacturing and materials cost.

4.2 Distributed expertise

As noted above there is no single expert for all of the aspects of composite design and manufacture. This distinguishes the type of system that is required for a solution to the problem from the typical expert system. Further there is a need to establish the sources of the expertise. These sources are both geographically and organizationally distributed. Some experts will belong to different organizations located at different places. For example, the experts in the design and use of composite materials may be government personnel attached to the CAV project (see below) while the experts in composite materials manufacturing simulation are government personnel attached to AMCOM and the engineering experts are professors at the University of Alabama in Huntsville and the University of Tulsa. This distribution of expertise makes the knowledge acquisition and knowledge engineering problem difficult. Additionally, it indicates the need for a system of communication. In our research thus far we have concentrated on building a common medium for the modular acquisition and engineering of knowledge and have made some tentative efforts toward attacking the communication system needed to bridge the geographical and organizational distribution of expertise and information sources.

4.3 Multiple intersecting fields of expertise

As noted above there are many intersecting areas of expertise. In a classical sense these would appear to be different domains. They would be different domains in the sense that each of the knowledge areas could function within a "closed world" assumption and in an automated system generate useful knowledge products. However, this is not a desirable state of affairs. Following the traditional approach each domain would be bounded by its "closed-world assumption" where this assumption would be represent in the typical values, default values, or explicit constraints for that knowledge area. A high level boundary condition might simply be a default that allows that if the design constraints are satisfied then the part is producible. Or that, a manufacturing modification of a design that simply substitute one material for another without an apparent loss of functionality will satisfy the design intent of the original part design. These sorts of constraints or defaults are often the ones that create the greatest difficulty in the life cycle process. On could

even make the case that if the life-cycle team-oriented approach is taken to the problem that all such boundaries should be soft boundaries. A boundary be considered soft if the information and knowledge form one domain can be used to alter the constraints and defaults of another domain.

Several traditional domains are relevant to the intent of the DTAME project. These include:

Materials experts
Design experts
Manufacturing experts
Economic and financial experts
Life-cycle experts
Environmental experts
Project experts.

At a basic level there is a need for knowledge about the actual materials used in the composite materials. These include but are not limited to the fibers and the resins. It should be noted that in many cases the resins are formulated in response to the design constraints. It should also be noted that the resin formulations are often within the province of a private corporation. Our efforts have indicated that it is extremely difficult to capture this sort of knowledge. It also appears that while some of the information in this area of expertise may be represented in a relational database, it is not at all clear that this will be the best approach. While there are lists of resins and fibers with some of their material properties, it remains the case that the manufacturer's experts will formulate the materials to a given specification. While this means that the materials may in a sense be COTS, they are also custom made COTS.

The foregoing suggests that the design expert will need to place specification on the materials to be used in production of the part. This is partially true. However, the design engineer will not always know whether the desired materials are available. Further, the design engineer will need to operate in two related areas. The first are is that of function design. The key question in this area is can, "Can a part be designed that will be capable of the function in the overall design?" This means that there is some overall design that provides the higher level functions from which the lower level functions are derived. The second are is that of mechanical design. The key question in this case is, "Can a part be designed that has acceptable mechanical characteristics?" This is a complex problem in the case of composite materials and becomes even more complex

in the case of laminated composite parts. The engineering analysis of such parts is much different than the engineering analysis of homogeneous non-layered parts. Even if the designer is able to construct the design it does not immediately follow that it can actually be built or can be built within other constraint for the project.

Manufacturing expertise may reside in any number of areas. Individuals in industry, government, and universities may each be a knowledge source for a particular kind of manufacturing. In composite materials design and manufacture there are a great many processes and many more will continue to be created. In this set of circumstances it is quite likely that, say, one corporation may have expertise in one type of manufacturing process but not in others. If the designers were working within a wholly "closed world assumption" they might not have a great deal of in formation about these processes on the trade-offs that might be made between them. The manufacturing engineers will have knowledge of the processes, may have knowledge of the trade-offs between, process, but may not be involved in the early portions of the life-cycle. Additionally the manufacturing component of the life-cycle will need to create simulations of the manufacturing process to determine if the process is feasible, if it satisfies additional constraints, and if it can satisfy production requirements.

While the engineering effort in the design and production of a product are substantial the current economic an financial environment make the are of cost expertise significant. From the cost of raw materials to the notions of management overhead the cost factors must be recognized and analyzed. This sort of expertise, information, and knowledge is distinct from that found in the more engineering-oriented parts of a project. Again this raise questions of distribution, modularization, and soft-boundaries. The success of a project may depend on these economic and financial considerations.

In order to fully evaluate the life cycle of a product or process, the discipline of life cycle analysis has emerged. This relatively new technique has its roots in the packaging industry, although it can be applied to any product or process. Life cycle analyses are typically performed to evaluate and compare the life cycles of competing products, such as the classic and familiar example of paper versus plastic grocery sacks. Only recently has the technique begun to be

applied in the design stage, or to durable (as opposed to disposable) products. To apply life cycle analysis in the design stage of an engineering project – as is appropriate in this system – requires the ability to predict the life cycle of a component that does not yet exist.

Life cycle analysis involves three main concerns: inventory, impact analysis, and improvement analysis. The life cycle of any manufactured component or system may be broken down into the following stages: (1) raw materials production, (2) manufacturing and assembly, (3) service life, and (4) Post-service (recycling/disposal). All of the activities, material flows, and energy flows in each stage of the life cycle must be accounted for in a proper life cycle inventory. Typically stored on an engineering spreadsheet, these inventories can be quite extensive. Several commercial databases exist that can aid in the inventory process by providing templates for the manufacture of various commodity materials such as steel, glass, chemical, etc. The inventory process is at the heart of life cycle analysis. It is tedious and time-consuming, and frequently calls upon the judgment of the life cycle analyst in allocating resources (especially in the case of consumer products, which are frequently use din a variety of different ways).

Theses new concerns for the use of objects over their life time has led to the development of experts about the product life-cycle. The life-cycle of the product may begin at the analysis of a problem, development of requirements, conceptual design, design, procurement, manufacture, distribution, storage, maintenance, and disposal. Many of these areas impinge on the design and production composite. Of special interest is the notion of disposal (post-service) since it may be very difficult to dispose of parts made from composite materials.

When a new materials system, such as any of the various types of advanced composites, is being considered for an application, numerous factors must be accounted for in the decision. These include traditional design considerations such as cost, weight, manufacturability, and so on, and are of the type already implemented in varying degrees in the systems we have prototyped. Increasingly, a variety of environmental issues are being added to the traditional list of design decision parameters. These environmental issues include the following:

- the use of non-renewable resources
- the ability to reuse or recycle a product or component
- air, water, and solid emissions resulting from the various stages of a product's life cycle
- the use of hazardous materials during the manufacturing process
- energy use throughout the life cycle.

Environmental factors have been considered as an intimate part of this project. These environmental factors are themselves multi-disciplinary. They bring together science, engineering, and regulation. In many ways it is this last element that is novel. The environmental expert brings the regulations that govern this area to bear. These regulations come in various forms but they are all sets of rules that govern the manufacturing and disposal processes. Further, it appears to be the case that the rules can vary from state to state and area to area.

Project management is the final area of expertise that needs to be considered. Although this may be the softest of the areas it is one that permeates all of the soft-boundaries of the foregoing areas of expertise. From decisions about schedules to decisions about priorities project management affects the ongoing parts of the product life-cycle. Again this are is distinct form the previous areas. The obvious difference lies in the need to make and justify decisions based on complex interactions with the external environment and the need to access knowledge and information about the project at the appropriate level of detail.

4.4 Multiple sets of constraints

The intersection of multiple fields of expertise give rise to a variety of constraints that must to some degree be satisfied. As we have seen in CDMCS there are not only degrees of satisfaction to be considered but also a typology of constraint. In our research efforts, we have represented constraints as metrics which allow for degrees of satisfaction with limited information and knowledge. Further it should be noted that while the metrics are easily grouped into domain-like clusters, there is no impenetrable barrier for the interaction of metrics across the clusters. This allows for the soft-boundaries required by the multiple interaction of domains of expertise, the distribution of expertise, and the focal problem.

The basic clusters of constraints include the following:

Geometrical
Mechanical
Chemical
Producibility
Cost
Environmental
Life-cycle.

Geometrical constraints are constraints on the form of the part, and are sensitive to the manufacturing process being examined. Mechanical constraints focus on the loading that the part will be subject to, and are, again, sensitive to the process being used. The chemical constraints focus on the interaction on the resin and fiber, the surface bonding characteristics of the manufactured object, and the environment in which the manufactured object will be used. Many of the chemical metrics will cut across manufacturing processes and will be sensitive to the materials that are used. Producibility constraint concern the ability of the manufacturing process to produce the specified object with in the bounds and tolerances specified in a design. Once again these metrics are sensitive to the process being used. Cost constraints focus on the variety of factors that affect the cost of the product. Materials, labor, location, scheduling, production quantities, post-production activities, and more can affect the cost. While these metrics will be sensitive to the process, they will also be sensitive to many other non-process factors. Environmental factors merge concerns about materials, safety, energy, and regulations across the life-cycle of the project. These metrics will be most sensitive to regulatory and life-cycle considerations. Life-cycle metrics focus on the factors that affect the project before, during, and after manufacturing. Life-cycle facts will be most sensitive to project management concerns.

4.5 New constraints

Constraints in the field of composite material design and manufacture are not fixed and continue to evolve. There is a continuing evolution of materials and processes. This evolution will lead to continuous change in the metrics and information for this area. The changes in this field create two important areas of investigation. The first is the way in which any automated tool can

respond to these changes. The second is the way in which an automated tools can assist and facilitate these changes.

The first point is typically handled by having all of the information and knowledge stored externally. We have taken this path in the systems we have been developing. However, there are some very important issue that have affected the development of this approach. While our intent is to focus on the network, we are confronted by the difficulty of having to access proprietary information. This is a challenge. Although we will continue to work on this problem, it is not likely that it will be easily solve. The second problem is that the information may simply not exist in a readily accessible electronic form. This is no where more evident than in the area of environmental regulations. In this area we have had some success in getting some information. However, the style of the digital databases make it virtually unusable without the corresponding "work-sheets" and printed materials. Unfortunately these are not in electronic form. Finally, information about economic and financial factors is closely guarded in many cases. This information is essential to the use of the metrics for various constraints.

We believe that a set of central information and knowledge sources accessed from local clients would be an important part of a general solution to the composite design and manufacture problem. These shared information and knowledge sources would be able to reflect the evolving nature of the area while providing for stability of the client software as well as consistency in the developmental use of the software. We will continue to investigate the best way in which such a solution can be design and, as possible and feasible, incorporate these features into the future evolution of the DTAME system.

4.6 Simulation

The simulation component is designed to uniquely integrates environmental, cost, quality, and production criteria into a modular simulation system for a given manufacturing domain. The modular simulation system obtains relevant information from the design engineer, efficiently models a variety of manufacturing options for the given manufacturing technology, and generates quality, environmental, cost, and production reports for use by the design engineer

when considering manufacturing alternatives. The developed methodology was the basis for a prototype modular simulation system for the filament winding composite manufacturing technology application.

4.7 Optimization

Genetic algorithms (GA) are being utilized for the optimization of the simulation process parameters. The optimization component takes as input a Witness simulation model. Process parameters such as cycle times, number of parallel machines, machine breakdowns, etc. are varied between simulation runs. The GA takes the results of the simulation run and evaluates the results in light of a predefined fitness function. This optimization methodology is used to determine the "best" settings for these process parameters.

4.8 Integration and communication

While various database tools can aid in the life-cycle process, there are no systems-level computer tools that aid the designer in applying life cycle analysis as a design tool. Much as, for example, finite element analysis has revolutionized the field of stress analysis, life cycle analysis could change the way that environmental issues are systematically evaluated during the design stage. A generic life cycle analysis tool modeled after aspects of the CDMCS, would represent a significant advance in the field of life cycle analysis and engineering design. Such a tool would be useful not only for composite materials, but all other kinds of materials as well.

To that end we have investigated concept known as the Design Tool for Assessing Manufacturing Environmental Impact (DTAME) which would be designed based on capabilities and systems developed in two previous research projects: a system used to critique the applicability of a particular composite manufacturing process and an interactive simulator developed to rapidly define, model, and evaluate electronic manufacturing systems. It would also utilize results from genetic algorithms research to optimize system configuration. DTAME will aid in making environmentally conscious decisions, and apply appropriate metrics and regulations within the normal context of simulation development and use to generate critiques of

proposed actions. Although the targeted domain is polymer based composite materials, the architecture of the proposed system is generic to allow for "plug and play" modularity.

The design focuses on the identification of parameters necessary to characterize the environmental and energy impact of key production processes. The output of such a simulation model will provide engineers and managers with information on system output, queue length, and production lead times as well as energy usage and the types and quantities of scrap and hazardous material produced. Another focus is on the development of capabilities to not only determine the absolute performance of the system (i.e., kilowatt hours of energy used per year, tons of hazardous material produced, etc.), but also allow users to say with a high degree of certainty which of two alternative systems is environmentally preferable.

For example, if an Integrated Product and Integrated Product Development Team (IPT/ IPDT), composed of personnel from multi-functional disciplines, is considering the design and manufacture of a motor casing. They are considering the design, producibility, and environmental concerns associated with the production of this system. DTAME will query the team about individual components in the system, including information about mechanical property requirements, production quantities, component size and shape, material preferences, processing preferences, etc. DTAME will interactively build a high level simulation model utilizing information from similar cases, its knowledge base, and remote databases containing regulations, specifications and standards. DTAME will assist in highlighting requirements with adverse environmental consequences and the manufacturing processes they would affect (i.e. cleaning). A simulation model will be developed that addresses the usual production performance metrics, but also provides environmental metrics (i.e. waste by-products, energy consumption, etc.) that are time sensitive aspects of a proposed production plan. Finally, DTAME will provide optimized production line requirements based on the design, manufacturing, and environmental factors.

It is anticipated that the scenario provided above will actually occur with the push toward "environmentally-friendly" missiles. SERDP's (Strategic Environmental Research and Development Program) Green Missile Initiative Developments, under the Pollution Prevention

pillar, is striving to encourage Project Managers to address environmental factors and concerns in their designs. Historically, Project Management Offices have been most concerned with the performance of a missile system and have not responded favorably to a trade-off between system performance and environmental concerns. However, there have been certain instances, such as the incorporation of a nitrogen based propellant, where certain aspects of system performance has actually increased when changes were made for environmental reasons. It is realized that increased system performance is not typically the outcome of such a change, but a tool like DTAME will allow project managers to consider the environmental and performance trade-offs.

5) Overview of a Solution

The modules of DTAME have been prototyped in parallel. The result is a mix of platforms and languages. However, there is a systematic approach to the construction. The flow of the operations would begin with CDMCS, continue to the static analyzer, be exercised in the simulation environment, and finally be submitted to for optimization. This set of operations will be supported by the system wide utilities that attempt to unify the interprogramatic interface and the user interface, and provide for communication among team members. Diagram 5.0.1 illustrates the general structure and flow.

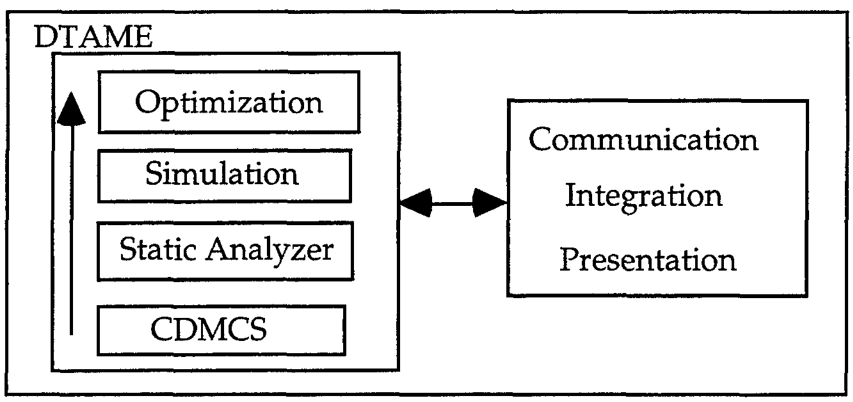


Diagram 5.0.1 DTAME Conceptual Architecture

5.1 CDMCS

Traditional expert systems efforts within AI have concentrated either on giving advice to an end-user or replacing the end-user. In the former case the knowledge in the system is used to guide the actions of the end-user, while in the latter case the knowledge of the expert, as captured in the system, is deemed of such a high quality that there is no need for the end-user to do any further processing. Another effort within traditional AI has been the construction of intelligent tutoring systems. In this research enterprise, the domain knowledge of the expert, as captured within the system, is used to train the end-user about a particular domain. Typically, the end-user is presented with scenarios on which he or she acts. The actions taken are recorded and compared to what the expert would have done, on the basis of that comparison errors are identified and explained, and the end-user is presented another scenario to improve his or her training level. Each of these AI approaches has value. However, in many situations neither approach is satisfactory. The experts system enterprise often fails to take into account multiple, "fuzzy" criteria for assessing the "goodness" of a solution, and often focuses its explanations on the line of reasoning that the system engaged. The intelligent tutoring enterprise is only concerned with the learning of the end-user and does not readily take into account that the end-user knows some things about the domain. These two weakness can be seen clearly when the task to which the AI system is put is an evaluative task. In such tasks the question is neither "Can a solution to a problem be found?" nor "Can the individual be trained to produce solutions?" Rather in an evaluative task the question is "How can a proposed solution be appraised?" This question calls for a strategy different than that found in the traditional expert systems and intelligent tutoring approaches. Systems that are designed to answer the appraisal question are critiquing systems.

Critiquing systems assume that the end-user knows something, and, perhaps a great deal, about the domain. It also assumes that the end-user has some notion of a solution to his or her problem, and that he or she can provide some data on which a solution is based. From the point of view of the critiquing system, the problem is to use the data to appraise the solution in terms of various appraisal criteria and provide the user with a report on the "goodness" of the proposed solution.

This report identifies and explains weaknesses and strengths, and indicates where and how improvements may be made.

CDMCS is designed in a hierarchical fashion, based on the concept of parameters, metrics, and process definitions. The system resides on the Macintosh platform, coded in Common LISP. The system is designed in a generic, user-friendly architecture that can ultimately be used for developing similar critiquing systems. The core of the system is comprised of definitions and terms (reference facilities), metrics concerning composites processing, process definitions, and computational facilities for metric aggregation. The user supplies parameter values for pertinent design data.

Appraisals involve the use of criteria by which the "goodness" of an item is determined. We understand the "goodness" of an item to be measured in terms of the degree to which some criterion is satisfied. These criteria are called metrics since they are measures of goodness. In some cases such metrics may be very clear and not admitting of degrees. Such metrics will be called requisite metrics. Requisite metrics correspond to the idea of necessary conditions in more traditional forms of analysis. Thus, if the requisite metrics are not satisfied, then the item is rejected. Additionally there are core metrics. These metrics are essential to the appraisal, but admit of degrees of satisfaction. These degrees of satisfaction are a measure of the "goodness" of an item, given the satisfaction of the requisite metrics. Finally, there are enabling metrics that can alter the basic "goodness" as measured by the core metrics in small ways. Together these three types of metrics are used to appraise an item. It should be clear that these metrics can be numerous and an aggregate appraisal is required in addition to the appraisal of an individual metric.

The key element for the computation of an appraisal is the idea of satisfaction. Satisfaction is the measure of the degree to which some data item is contained in a metric. In the sense in which we are using the term, satisfaction can be described as follows:

the item I satisfies the metric M to the degree D just in case

(1) the M applies to I
(2) there is some function F_I that generates D from I and M

In aggregation the notion of satisfaction is extended to multiple metrics as follows:

a collection of metrics {M} relative to a process P has an aggregate value V just in case

(1) there are a set of metrics {M} defined for the process P
(2) the metric M_i of {M} is satisfied to the degree D_i according to the previous definition
(3) the metrics in {M} are categorized as requisite, core, and enabling
(4) if any requisite or core metric in {M} has a value of 0, then the aggregate value is 0; otherwise

(5) the aggregate value $V = V_{Core} + V_{Enabling}$ where

V_{Core} is given by a function F_C that sums the values of the core metrics, and

$V_{Enabling}$ is given by a function F_E that adds or subtracts incremental values relative to V_{core}.

5.2 Witness Model Development

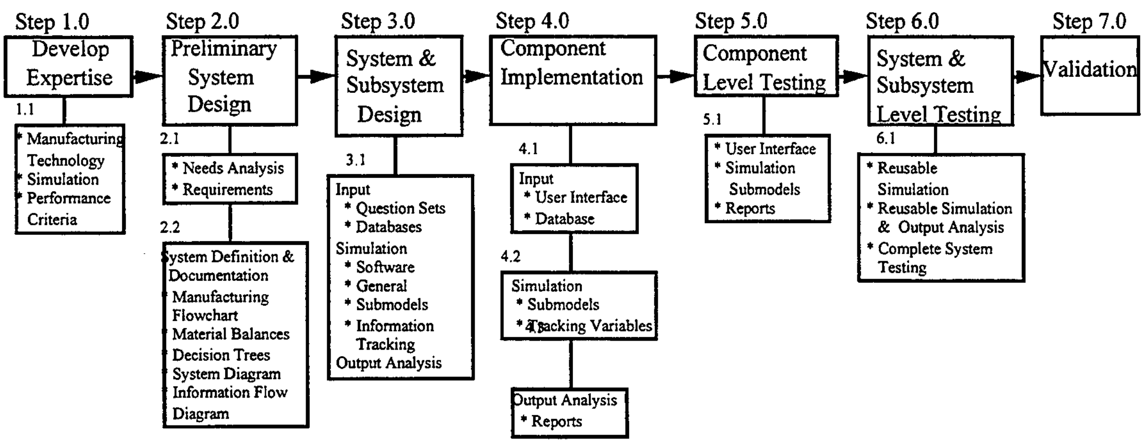


Figure 5.2.1 Flow Diagram of Methodology for Designing and Developing a Modular Multi-Criteria Discrete Event Simulation

In this section a description of the developed methodology will be applied to the filament winding manufacturing technology. This is intended to show the viability of the methodology

and aid in the application of the methodology to other real world situations. The developed methodology is shown in Figure 5.2.1.

Developing Expertise (Step 1.0)

Designing and building the modular multi-criteria simulation for this application required expertise in 1) filament winding manufacturing technology, 2) general simulation methods and WITNESS simulation environment, and 3) environmental, quality, and process performance criteria. Although a team approach could be used to bring together these areas of expertise this application was developed individually with the help of many experts, particularly in the field of composite manufacturing. Key resources and topics which contributed greatly to both developing the general methodology and completing this application include:

1) Life cycle design concepts, methods, and tools.
2) Waste minimization techniques.
3) General composite manufacturing.
4) Environmental issues regarding composite manufacturing.
5) Filament winding technology.
6) Simulation research.

Preliminary System Design (Step 2.0)

Needs Analysis

Conducting a needs analysis is the first step in the preliminary system design phase and includes the purpose, scope, and customers of the system. In Figure 5.2.2 the structure of the advanced composites industry is shown to illustrate the scope of the system. The diagram includes the fiber and resin suppliers, prepreggers, fabricators, and end users. This application will address the "Fabricator" box in the middle of the diagram. One of the important assumptions is that the products being produced will be similar. Therefore, most effects of the product, from raw material acquisition and production to retirement and disposal, will also be similar and do not need to be analyzed separately. If this assumption is not correct it becomes readily apparent that life cycle design becomes an extremely complex task which can be aided, but not completely analyzed, through the use of this simulation model. In summary, the simulation being developed is designed to compare two similar products which can be fabricated in different ways and to select the better fabrication method based on multiple criteria.

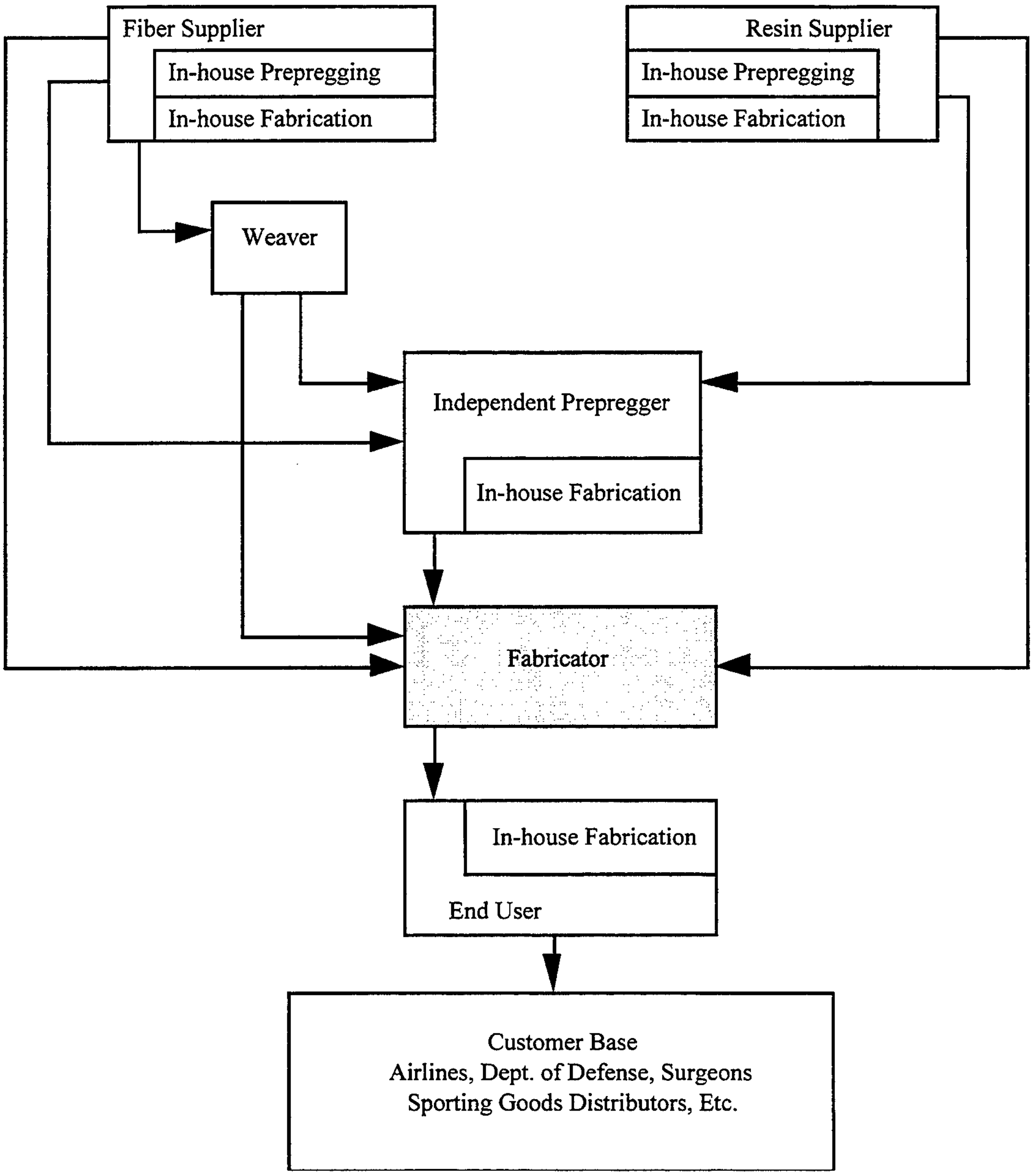


Figure 5.2.2 Structure of the Advanced Composite Industry
[Advanced Composites Bluebook, 1993]

The design engineer has many customers whose needs must be addressed during this step. Potential customers include individuals who manufacture the product, individuals who use and maintain the product, the government, and society. In order to meet these customer's needs, quality, maintainability, manufacturability, reliability, environmental, and legal issues must be addressed as a system of requirements. This view portrays the complex nature of product design.

The primary customer or user of the modular simulation was viewed as a design engineer with a minimum of 2-3 years of experience. Other secondary customers who would be responsible for maintaining, updating, and customizing the simulation system were also considered. Because each user would eventually have to develop an individual needs analysis for their design project based on their current policies concerning the environment, customers, quality, and cost, it was important that the simulation model be able to support the varying information needs of its users. The scope of the project was limited to production facilities which produce one product in a mass production environment. Although there are unlimited modifications to the design of the manufacturing process that could be considered during the design phase, certain restrictions existed based on the limitations of discrete event simulators and the amount of time and resources allotted to the project. With these considerations in mind the needs analysis below was developed.

This simulation model must:

1. Be relatively easy to use for a design engineer with 2-3 years of experience. Questions should be extensive enough to obtain required information, but not so extensive that the model is not used.

2. Have a wide range of application. The model should be of assistance to companies fabricating a limited number of parts (25-50) as well as mass production facilities.

3. Be able to be modified by experienced simulation users.

4. Generate information on production, environmental, quality, and cost performance.

5. Be reusable within limits for various modifications within the fabrication process. These modifications should include but not be limited to differences in type of materials used, configuration, process and maintenance times, labor usage, and processing steps.

6. Be valid for differentiating between manufacturing alternatives.

7. Have the ability to adapt design criteria to changing business environments.

8. Be available to be used for manufacturing process evaluation from the conceptual through the preliminary design phase.

9. Be limited in scope to the fabrication stage of the product life cycle.

Requirements

Formulating requirements is the next phase of the development process. Requirements flow from the needs analysis and feed the design phase. Figure 5.2.3 shows the conceptual requirements matrices from the Life Cycle Design Guidance Manual published by the EPA with some examples from the composite industry. The highlighted square is the area specifically being addressed in this simulation model; however the simulation will indirectly contribute to the understanding of all the squares in the first two rows. These requirements should be driven by the requirements which the design engineer faces during the design of the manufacturing process.

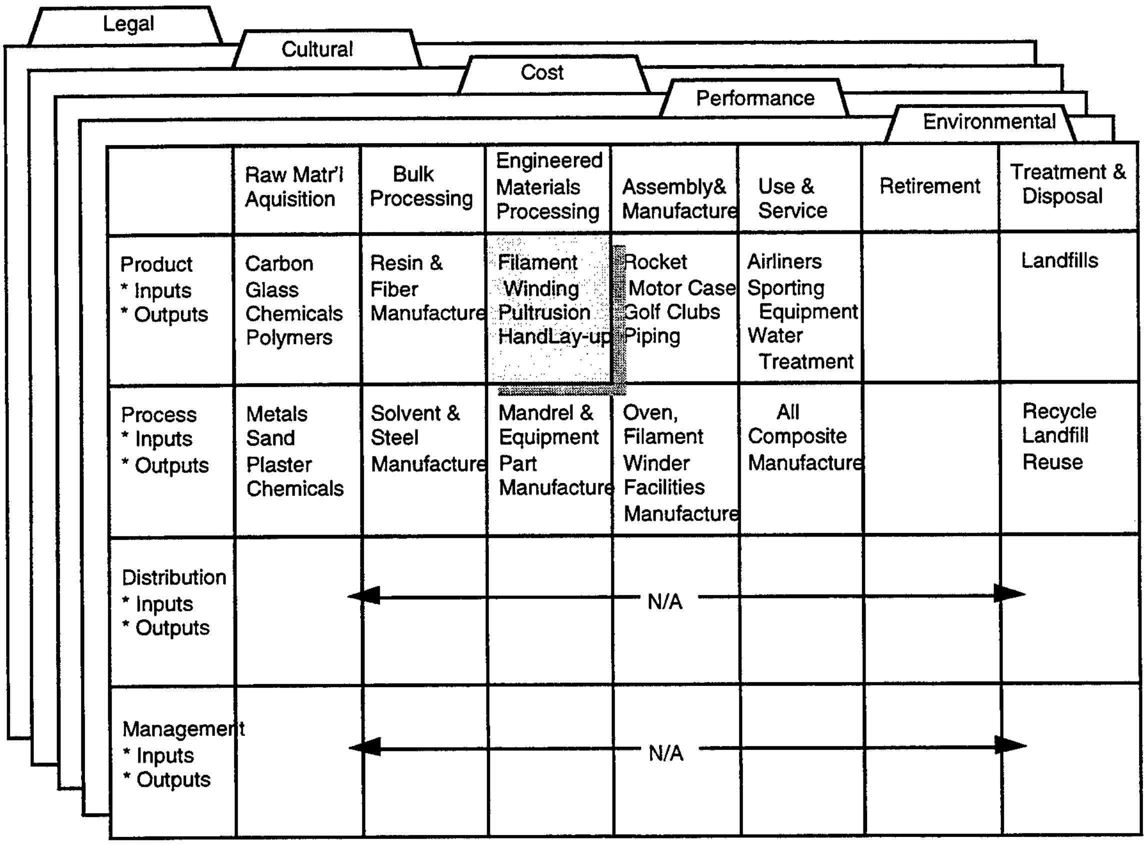


Figure 5.2.3 Conceptual Requirements Matrix - Examples from Composite Industry [Keoleian and Menerey, 1993]

Although information on all of these requirements may be of some value, the information is not of equal importance. It may be necessary for users to tailor the information to particular needs by utilizing various multi-criteria decision making models.

System Definition and Documentation

After detailed discussions with individuals knowledgeable in composite processing, the flowchart given in Figure 5.2.4 was developed. This flowchart was used extensively throughout the design of the filament winding simulation system. A filament winding manufacturing process consists of up to six main process steps which include mandrel preparation, filament winding, curing, mandrel removal, finishing, and quality inspection.

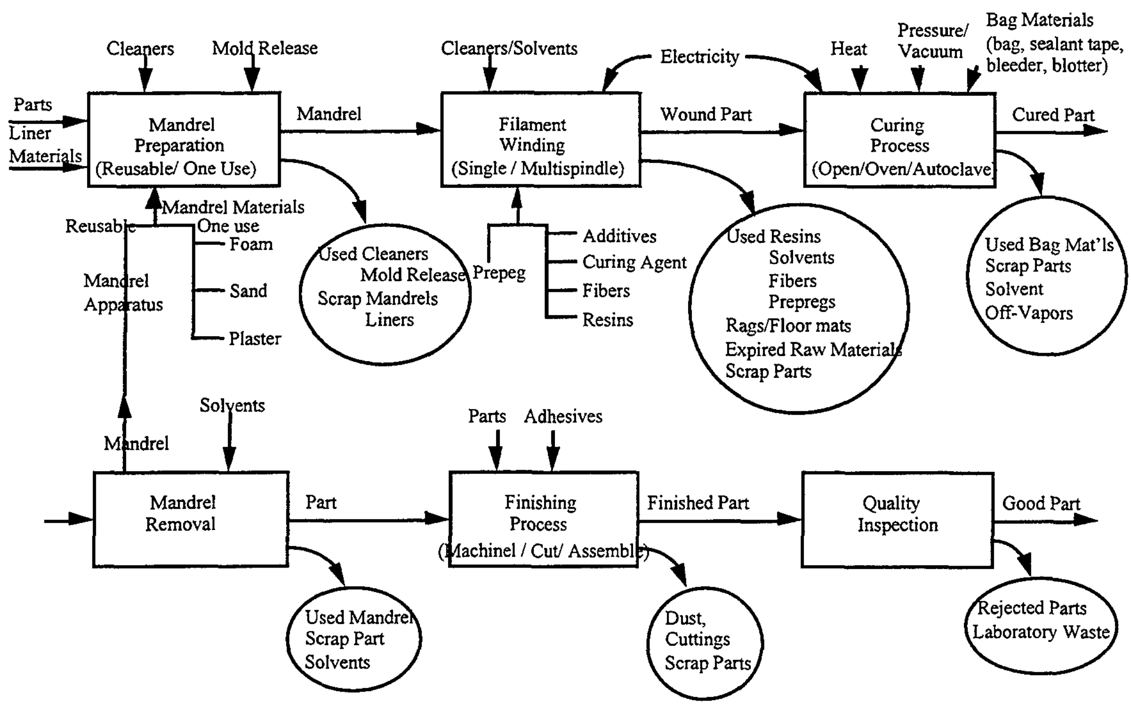


Figure 5.2.4 Filament Winding Flowchart

The first step is mandrel preparation where either a one use or reusable mandrel is placed on a reusable arbor and prepared. The mandrel preparation normally includes one or more of the following:

1) mold release can be applied to the mandrel.
2) the mandrel can be cleaned.
3) a liner can be applied to the mandrel.
4) parts can be attached to the mandrel.

The second step, filament winding, is where composite materials are wound around a prepared mandrel. Wet or prepreg composite materials can be used during filament winding. In wet winding the fiber is covered by a mixture of resin, a curing agent, and various additives and placed firmly around a rotating mandrel. During wet winding the machine must be cleaned with a solvent approximately every eight hours so the resin mixture does not set up. Prepreg composite materials come in a precured state with the fibers and resin mixture already combined. Although prepreg materials are much easier to work with, they are also more expensive.

The third stage, curing, is done either at room temperature, in an oven, or in an autoclave depending on the resin mixture and the design of the part. Processing can be either batch or continuous. If an autoclave is used, parts must be enclosed in a bag for protection, with bag materials discarded after each use. Reusable bags, however, can be special ordered which are tailor made for the composite part. Curing can also occur in two stages, pre and post cure. These stages may use any of the above curing methods.

In the fourth stage the mandrels and arbors are removed from the cured part. The arbors and reusable mandrels are sent back to mandrel preparation to be used again. One use mandrels are discarded after mandrel removal. Solvents may also be necessary to aid in the removal of some "one use" mandrels.

The finishing process includes three different types of operations: machining, cutting, and assembling. Machining is any process which removes material from the part. Cutting is where the original part is cut into any number of equal sized smaller parts. Assembly is any process which attaches other parts to the existing part. These operations can be simulated in any order. Machining can be done either before or after mandrel removal.

Quality inspection, the last step in the process, allows parts to be inspected individually or in a batch. Materials used in laboratory testing are not accounted for during this step. All poor quality parts (scrap) are assumed to be discarded as soon as they are produced. This implies that discarded parts are visually inspected during processing. Poor quality parts (scrap) which can not be visually inspected must be carried through to the quality inspection process. The processing step which produced the poor quality part is unknown for all parts scrapped during quality inspection.

The interface between the simulation and the user input is the other design consideration addressed during this phase. Decision tree diagrams were developed for each process step to illustrate how key decisions impact the selection of submodels and question sets. A one-to-one relationship between submodels and question sets is not necessary. The filament winding application illustrates this lack of a one-to-one relationship for both the mandrel preparation process and curing process. The decision tree diagram used for the mandrel preparation process step (Figure 5.2.5) shows that "mandrel type" is a key decision which effects which question set will be answered for mandrel preparation. If reusable mandrels are used then Question Set 2-1 will need to be answered and Submodel 2-1 will be used for the simulation. If one use mandrels are used Question Set 2-2 will need to be answered; however, the same submodel is used for the simulation. The two question sets differ only in the type of questions asked pertaining to the mandrels themselves. Similar diagrams for the other process steps and the associated questions sets can be found in Appendix A.

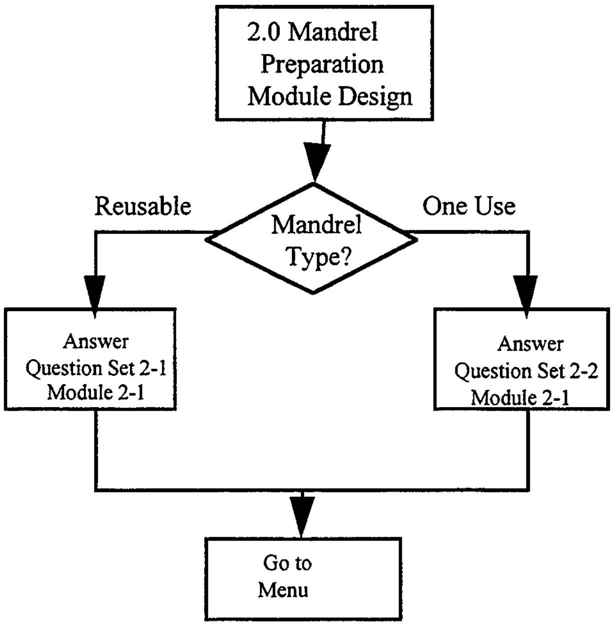
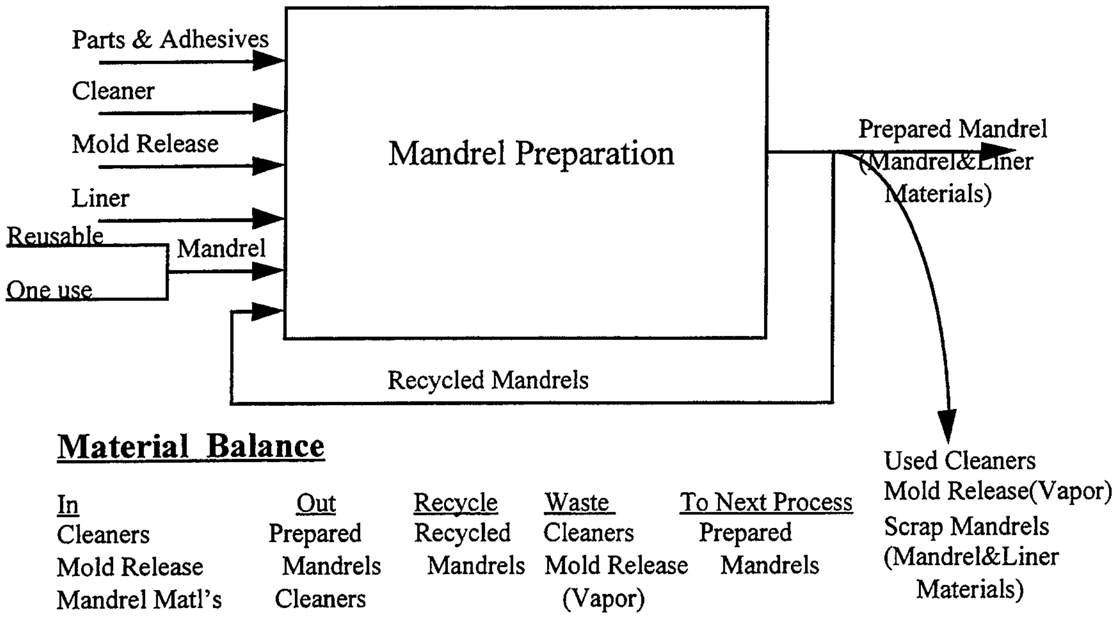


Figure 5.2.5 Mandrel Preparation Decision Tree Diagram

Along with the flowchart, a general material balance and flow diagram were developed for each process step or submodel. The material balance and flow diagram developed for the mandrel preparation process are shown in Figure 5.2.6. The diagram shows all the input, output, and recycle streams for the mandrel preparation step. General material balance equations which consist of all the input and output streams for each material category are also shown. Some categories of materials will have the same general equations for some of the process steps (i.e., liner, parts, and mandrel materials). For example, the materials used for the liners, parts, and mandrels all enter the submodel as raw materials. These materials can leave the submodel as either discarded raw material, scrap, or prepared mandrels. It is important to remember that these are general equations and that each manufacturing scenario will have its own individual set of equations depending on the materials and the order of submodels utilized for the analysis. One of the most difficult aspects of developing the system was to make sure that the system would automatically use the proper equations for each manufacturing option.



Material Balance

In	Out	Recycle	Waste	To Next Process
Cleaners	Prepared Mandrels	Recycled Mandrels	Cleaners	Prepared Mandrels
Mold Release	Cleaners		Mold Release (Vapor)	
Mandrel Matl's	Mold Release (Vapor)		Scrap Mandrels	
Liner Matl's	Scrap Mandrels			
Parts				
Adhesives				

Equations

X designates amount of material coming into submodel
Y designates amount of material leaving submodel

Cleaners: $X_{nc} + X_{rc} = Y_{wc} + Y_{rc}$ where:
X_{nc} = New Cleaners
X_{rc} = Recycled Cleaners
Y_{wc} = Waste Cleaners
Y_{rc} = Recycled Cleaners

Mold Release: $X_{mr} = Y_{wmr} + Y_{dmr}$ where:
X_{mr} = Mold Release coming in
Y_{wmr} = Waste Mold Release
Y_{dmr} = Mold Release discarded as raw material

Liner, Parts and Mandrel Materials: $X_m = Y_{pm} + Y_{sm} + Y_{drm}$ where:
X_m = Mat'ls coming in
Y_{pm} = Mat'ls in prepared mandrel
Y_{sm} = Mat'ls in scrap mandrel
Y_{drm} = Mat'ls discarded as raw material

Figure 5.2.6 Flowchart and Material Balance for Mandrel Preparation Step

The next step was to define the system, subsystems, and components of the filament winding simulation system. A detailed system diagram (Figure 5.2.7), was developed for the filament winding simulation. As more knowledge was gained about the filament winding process, the system diagram became more specific and more detailed.

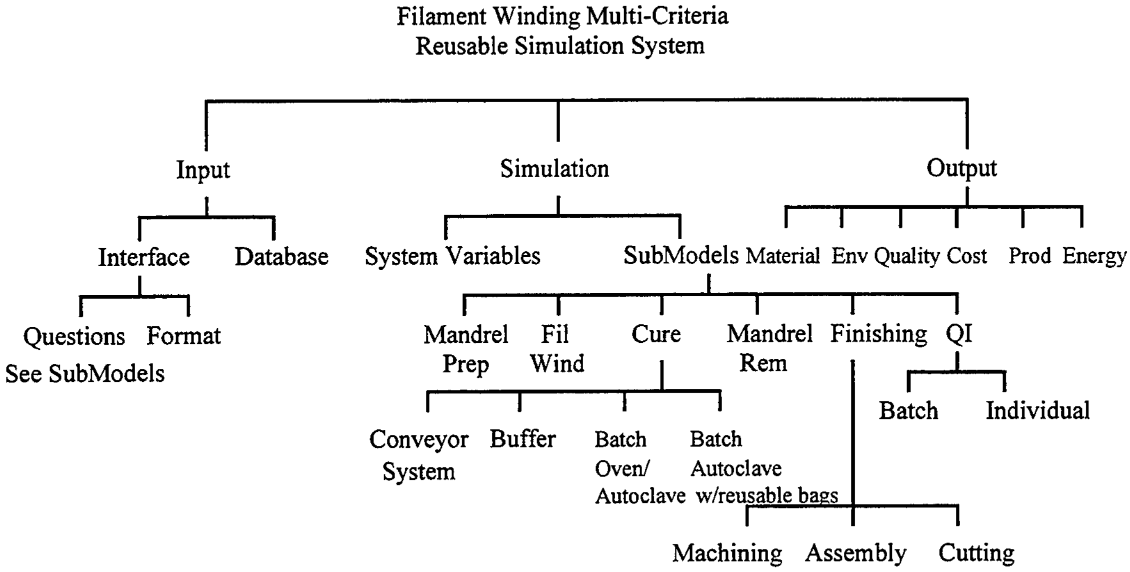


Figure 5.2.7 System Diagram for Filament Winding Simulation System

The filament winding multi-criteria modular simulation system is composed of three subsystems, the input system, the simulation, and the output system. The purpose of the input system is to ensure that all required information is obtained from the user and available for use within the system. This includes developing the format and questions for the user interface and the databases used to store user input data. The second subsystem is the simulation. The simulation subsystem uses the information obtained from the user to develop and run the simulation model and to generate information needed for the output subsystem. This includes developing submodels for all the process steps and creating system variables which will track the required information. For this application, there were a total of six main process steps (mandrel preparation, filament winding, curing, mandrel removal, finishing, and quality inspection) and a total of twelve distinct submodels. Mandrel preparation, filament winding, and mandrel removal required only one submodel each. The variety of processing methods available for curing, finishing, and quality inspection dictated the use of four, three, and two submodels, respectively. The output subsystem utilizes information from the user and the simulation to generate material, environmental, quality, cost, production, and energy reports.

The overall assumptions for the filament winding simulation are provided in Appendix B. The key assumptions for the filament winding model include: 1) the equipment is dedicated to processing one type of part, 2) all raw materials are available when needed, 3) general labor can be assigned to all manufacturing tasks, 4) all machine operations (i.e., cycle time, time between failure, set up times, etc.) are the same for all machines with a similar function, 5) a twenty-four hour work schedule is used for all machines, and 6) parts are sent directly from one process step to another.

Subsystem Design (Step 3.0)

Input Subsystem Design

Many different issues need to be considered during the development of the input subsystem. The preliminary question sets were developed for the filament winding application using the filament winding flowchart (Figure 5.2.4), the process flowcharts and material balances for the individual process steps, the detailing menus for the elements in the WITNESS simulation software, and the needs and requirements analyses. All four of these references helped guide which general categories of questions should be asked and what types of specific questions could be and should be allowed. The flowcharts and material balances were useful primarily with the questions concerning materials, while the WITNESS software was useful primarily with the questions concerning processing. All materials included in the flowchart had to be included in at least one of the questions sets. The WITNESS software not only helped decide which questions to include, but also helped determine what questions should not be included because of the limitations of the software. The questions fell into nine general categories including materials, labor, breakdowns, scheduled maintenance, set-up procedures, cycle time, energy usage, configuration, and quality. Not all categories are included in each question set because of 1) the differences in modeling the main process elements (oven vs. conveyor) and 2) the absence of material and energy usage during certain process steps. All the question sets used for the filament winding application are provided in Appendix A.

Most general purpose simulation software packages assume a user with a broader statistical background than the user of this developed system. Also, because this system is to be used primarily during the design stage, the users may be limited in the amount of information they can

obtain. These considerations had to be balanced with what information was needed from the user to obtain reasonable estimates from the simulation model.

The user input is used directly in the simulation or stored for future use in the material database or miscellaneous database. A preliminary design of the material database was completed during this phase including the database configuration, the number of materials to be included, and the type of information to be stored for each material.

Simulation Subsystem Design

Software Selection:

The selection of simulation software was an important aspect of the filament winding project. WITNESS [Lanner Group] was the simulation software selected for this research effort. The reasons for selecting WITNESS are outlined below:

1) Cost/Availability. The University of Alabama in Huntsville had already purchased several copies of WITNESS for another project. A technical support agreement which included an information hotline was also included with the software.

2) Ease of use. WITNESS is very user friendly and easy to learn because of its Windows based format.

3) Reusable design capability. WITNESS allows for design, storage, and retrieval of submodels which makes designing for reusability much easier.

4) Flexibility. WITNESS has a wide variety of options available to the user. This includes the ability to model both discrete and continuous processes, a wide variety of machine options, and the capability of customizing actions and functions.

5) Data transfer and access. WITNESS allows the user to run the simulation automatically from a command input file using the WITNESS command language (WCL). It is also compatible with the Microsoft Visual Basic programming language which would allow the model to be expanded to include automatic user interfaces and more elaborate output reporting capabilities.

Design

During simulation design each of the filament winding process steps were evaluated individually with regard to how they should be modeled. It was determined that most of the material usages would be calculated in the output reports by multiplying variables already available in

WITNESS by some constant usage rate entered by the user. For example, if X amount of resin is used for the processing of each composite part, then X would be multiplied by the number of parts processed in the filament winding machine to determine the total amount of resin required. Solvents used for cleaning during the filament winding operation are tracked through the use of variables which are designed into the simulation model. For example, "Solv1use" is the total amount of solvent 1 used for cleaning the filament winder. Each time cleaning occurred "Solv1use" is incremented by the amount "Solv1add." "Solv1add" is determined by sampling from a user defined distribution each time cleaning occurs. The only simulated "parts" are the mandrel, the reusable bags, and the part itself in its various stages of production. These decisions simplified the simulation and reduced the number of submodels needed for each processing step.

The final simulation includes only one submodel for mandrel preparation, filament winding, and mandrel removal. The curing process required four different submodels. The first is a conveyor which can be heated or at room-temperature; the second is a buffer-like stage where the part is cured at room temperature for a minimum amount of time; the third submodel is a batch cure using an oven or an autoclave with one-use bags; and the fourth submodel is a batch autoclave with reusable bags. The finishing process consisted of three operations including machining the part, cutting the part into a number of smaller equal sized parts, and assembling other parts to the filament wound part. Both the cutting and machining operations allow a percentage of the original part to be discarded as waste. Quality inspection required two submodels: 1) individual inspection where individual parts are inspected using non-destructive testing and, 2) batch inspection where a sample of parts are chosen from a batch and inspected using destructive testing. If the quality of the sample is found to be unacceptable during batch inspection, the entire batch is scrapped.

The possible placement of the submodels within the simulation was decided based on consultation with numerous composite manufacturing experts, visits to production facilities, and reviews of both journal and sales literature. The two main options are shown in Figure 5.2.8. Option 1 begins with the mandrel preparation and filament winding which are both required steps. The part then goes to a curing process which can be any of the four previously discussed submodels. The mandrel is then removed. From the simulation's viewpoint, mandrel removal is

the last required processing step. The part can then be sent to curing, finishing, quality inspection, or shipping. If a post cure is required the part is sent to another curing process. After curing it can be sent to finishing, quality inspection, or shipping. Any or all of the submodels can be used in any order for both the finishing and quality inspection

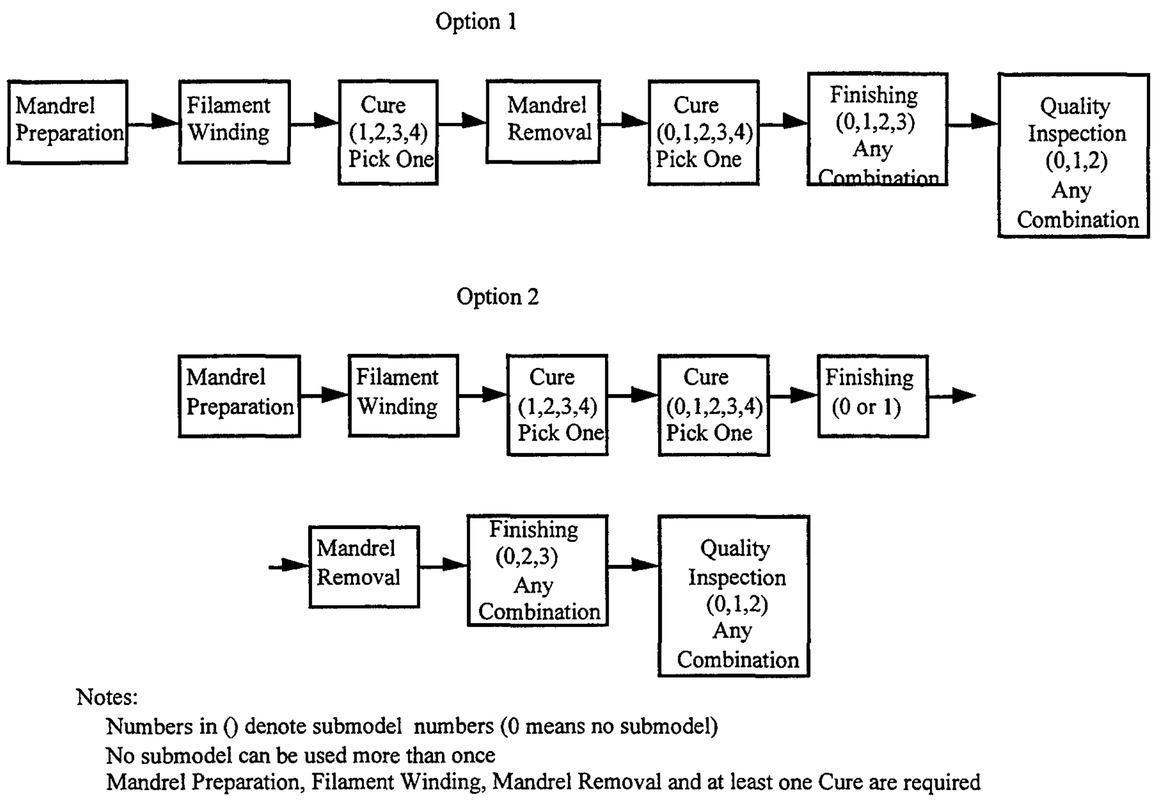


Figure 5.2.8 Diagram of Two Filament Winding Manufacturing Options

processing steps. All curing must be completed before finishing is started, and all finishing must be completed before quality inspection is performed. The inherent difficulties in tracking all materials in and out of a submodel dictates that a submodel can be used only once in a simulation.

Option 2 allows the part to be post-cured and machined (one of the three finishing operations) before mandrel removal is performed. Mandrel removal is still the last required operation. From mandrel removal the part proceeds to the other two finishing operations, quality inspection, or shipping.

The final aspect of simulation design included in this phase is determining how the simulation will gather all the data required to generate the output reports. The manufacturing placement options and material balance flows for all options must be taken into consideration. For the filament winding example, the number of scrap parts with varying compositions were tracked using variables which were incremented depending on which process steps had been completed. For example, there were ten variables which were utilized in the three finishing submodels for tracking the number of scrapped parts. These variables were then multiplied by the amount of material in each of the scrapped parts to determine the total amount of material discarded in that output stream. Part attributes (Assem, Cut, Mach) were used to track which finishing operations had taken place and in which sequence. These attributes were also used to determine which scrap variables were incremented at the completion of each of the finishing operations. The scrap variables are described below:

ScrapF0 and ScrapF1 are variables which track assembly materials and are utilized when the assembly submodel is included in the simulation.

ScrapF0: If Assem>0 and Assem<Cut, increment ScrapF0 by 1.
Tracks assembly materials and parts only.
Part was assembled before being cut.
To calculate the amount of material discarded as scrap in this output stream use the equation:

$$\text{ScrapF0} \times X_0/Y$$

where:

X_0 = Amount of material in original part.
Y = number of equal sized parts made from original part.

ScrapF1: If Assem>0 and Assem>Cut, increment ScrapF1 by 1.
Tracks assembly materials and parts only.
Part was assembled after being cut.
To calculate the amount of material discarded as scrap in this output stream use the equation:

$$\text{ScrapF1} \times X_0$$

where:

X_0 = Amount of material in original part.

ScrapF2, ScrapF3, ScrapF4, and ScrapF5 track the materials which are in the original part such as composite and liner materials. These materials could be cut, machined, and thrown away as waste during both the cutting and machining operation, but are were not effected by assembly.

ScrapF2: If Mach>1 and Cut=0, increment ScrapF2 by 1.
Part has been machined but not cut.
To calculate the amount of material discarded as scrap in this output stream use the equation:

ScrapF2 $\times$ (X_o-D_m)
where:
X_o = Amount of material in original part.
D_m= Amount of material discarded during machining operation.

ScrapF3 = If Mach=0 and Cut>1, increment ScrapF3 by 1.
Part has been cut but not machined.
To calculate the amount of material discarded as scrap in this output stream use the equation:
ScrapF3 $\times$ (X_o-D_c)/Y
where:
X_o= Amount of material in original part.
D_c= Amount of material discarded during cutting operation.
Y = number of equal sized parts made from original part.

ScrapF4 = If Mach>1 and Cut>1, increment ScrapF4 by 1.
Part has been machined and cut.
To calculate the amount of material discarded as scrap in this output stream use the equation:

ScrapF4 $\times$ (X_o-(D_c + D_m))/Y
where:
X_o= Amount of material in original part.
D_c= Amount of material discarded during cutting operation.
D_m= Amount of material discarded during machining operation.
Y = number of equal sized parts made from original part.

ScrapF5 = If Mach=0 and Cut=0, increment ScrapF5 by 1
Part has not been machined nor cut.
To calculate the amount of material discarded as scrap in this output stream use the equation:

$\text{ScrapF5} \times X_o$

where:

X_0= Amount of material in original part.

ScrapMa, ScrapA, and ScrapCut are variables which track the number of scrap parts for each of the finishing operations. These variables are used for verification purposes and in some logic expressions for the output report.

ScrapMa= Number of scrap parts from machining operation.

ScrapA = Number of scrap parts from assembly operation.

ScrapCut = Number of scrap parts from cutting operation.

ScrapF was a counter for all scrapped parts discarded during the finishing operations if mandrel removal had already taken place. This variable was used for logic expressions in the material reports to indicate if the mandrel removal input stream included parts which had been machined.

ScrapF = Counter for all finishing if mandrel removal has already taken place.
A list of all the variables, attributes, and definitions are provided in Appendix C.

Output Subsystem Design

The output design stage identifies what information will be reported, how the reports will be organized and displayed, and what numerical format and units will be used. For the filament winding example the requirements were used to begin this process. Six basic reports were developed: 1) the material report which includes the amount of each material that enters the system, exits the system in each output stream (good parts, mandrel prep scrap, etc.) and remains in the system as work in process, 2) the process report (from WITNESS), 3) the quality report which includes the amount and cost of all scrapped materials by processing station and type of material, 4) the environmental report which includes the amount and cost of all materials discarded as waste, 5) the energy report which includes the amount and cost of the energy used to produce the parts, and 6) the cost report which includes material, energy, and labor costs for producing the parts.

Component Implementation (Step 4.0)

Input Implementation

Design considerations at this point include issues concerning any modification required for the question sets, the format of the user interface, transfer of the user input to the databases or simulation software, and the user input databases. An example question set for the mandrel preparation step utilizing reusable mandrels is given below. The final version of all the question sets are provided in Appendix A.

Mandrel Preparation
Question Set 2-1

Materials

Mold Release Yes___ No (X) If yes: Name list/ insert MSDS info/cost
Amount used per mandrel (0)______
% discarded as unused mold release(0)_______

Liner Mat'ls Yes___ No (X) If yes: How many materials used(0)_______[0,1,2]
Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
% discarded as unused raw material(0)_______

Parts Yes___No(X) If yes: How many different parts used(0)______[0,1,2]
Name list/ insert MSDS info/cost
Number used per assembly(0)______
Weight(0)______
% discarded as unused parts(0)______

Adhesives Yes___ No (X) If yes: How many materials used(0)_______[0,1,2]
Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
% discarded as unused raw material(0)_______

Cleaner(for cleaning mandrels) Yes___ No (X) If yes: Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
Recycled Yes (X) No____
% Recycled 0-100%
% Released to Air 0-(100-%Recycled)
% Solid/liquid waste (100-[%Recycled + %Vapor])

Mandrels
Number Available(1000)_______
Cost(0)_______
Weight(0)_______

How many uses before discarding?(1000)________[deterministic or probabilistic]

Do scrap parts during mandrel preparation need to go to mandrel removal station for disassembly? Yes____No(X)

Labor

Is labor required? Yes (X)No____ If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes___No (X)

If yes: Frequency? time between breakdowns

Labor? Type general/(maintenance) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)

If yes: How many different types? 1-10

For each type: Frequency? time between breakdowns

Labor? (maintenance assumed) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Set up Procedures

Any set up procedures? Yes___ No (X)

If yes: Frequency of setup? # of cycles between setups

Labor? Type general/(maintenance) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Cycle Time

Cycle time? Type (deterministic)/triangular/probabilistic Parameters _________

Energy Usage

Energy Usage? Yes___No (X) If yes: Rate? Kw

Configuration

\# of Machines? (1)-20

Batch Size?(1)___

Quality

% Scrap? (0)-100%

% Recycle? (0)-[100- % Scrap]%

% Good Parts equals [100-[% Scrap + % Recycle]

For this application, user input is stored in the material database and the miscellaneous database (Appendix D) . The material database consists of the general material section and the option

specific section. The general material section stores general information about the materials including: the name of the material, material cost, and Material Safety Data Sheet (MSDS) environmental information.

The option specific section includes information required by the system each time a different experiment is run. This includes the amount of material used for the original part, the percentage of the part discarded during the cutting and machining operations, the percentage of the solvents recycled, and the percentage of the solvents evaporating into the air. This information must be included in the question sets for the appropriate submodels. For example, all questions concerning the composite materials used during the filament winding process step, such as resin and fiber, is included in the questionnaire used for the filament winding submodel.

The miscellaneous database contains information which did not "fit" in the material database but was needed for output report calculations. Information on batch sizes, energy costs, and number of parts shipped were included.

Simulation Submodel Implementation

After reviewing the type of processing which was to be performed by each submodel, the appropriate main process elements, buffers, parts, and variables were designed into each submodel. A list of the submodel element information used for the filament winding application is provided in Table 5.2.1. The first column provides the names of each of the submodels. The second column provides the names of the buffers used for each submodel. Some submodels do not include buffers because of the type of main process element used (i.e., cure1's conveyor). Some submodels have two buffers, one for the primary part and another recycle buffer for recycled parts (i.e., manprep1, cure4). The third column shows the name and type of main process element used for the submodel. Various types of machines (i.e., batch, general, production) had to be used to effectively model the various process steps. A conveyor and wait buffer are also used for two of the submodels. Cure2 uses both a wait buffer and a single machine. The single machine, however, is a dummy machine which includes the actions and output rules for the submodel. This is required since buffers are not allowed to include any actions in WITNESS. The fourth column includes the name of any parts processed in the

submodel. The primary part changes its name as it moves through the manufacturing process. The name of the quality distribution used to assign quality values to parts leaving the submodel's main process element is shown in column 5. The names of the variables used to track information in each submodel are given in columns 6-8. The ship variables which track the number of finished parts leaving the submodel are given in column 7.

The scrap variables which track the number of scrapped parts leaving the submodel are given in column 8. Any variables that are used that do not fit into either of these categories are given in column 6. All of the variables and their definitions are provided in Appendix C. The ninth column shows the type of labor available, general and maintenance, for all submodels. The last column shows the attribute group used for the parts in the submodels with the first group assigning attributes to the processed part and the second group only used during cure4 to assign attributes "UsesB" and "BagUses" to reusable bags. a list of these attributes and their definitions are provided in Appendix C.

The more difficult aspect of designing the submodels involved the logic used for the actions and output rules included in the submodels. The WITNESS library file for the details of the mandrel preparation step with written comments can be found below:

Witness Library Detail File for Mandrel Prep1

Manprep1

This submodel models the mandrel preparation operation. It contains three basic elements, the new mandrel buffer (MandBuff) and the recycled mandrel buffer (MandRec), two FIFO queues, and the mandrel preparation machine (MandPrep1), a batch machine with a default batch size of 1. The default machine has no setup and experiences no breakdowns. The user has the option of choosing general labor or no labor for the mandrel prep operation. New and reused mandrels enter the MandBuff while mandrels recycled during this operation are stored in MandRec. MandPrep1 can pull a mandrel from either buffer to begin the mandrel preparation (preference

goes to MandRec). The following actions are initiated upon completion of the mandrel preparation operation:

ACTIONS, Finish

IF Uses = 0 AND Quality = 0
ManUses = NEGEXP (200,57)
ENDIF

[If mandrel quality is good and Uses (the number of times the mandrel has been used) is equal to zero, assign a new value of ManUses (the number of times the mandrel can be used). This is used to assign a value of Manuses to original mandrels.]

IF Uses > ManUses AND Quality = 0
NewMand = NewMand + 1
Uses = 0
ManUses = NEGEXP (200,57)
ENDIF

[If Uses (the number of times that the mandrel has been used) is greater than ManUses (the number of times the mandrel can be used) and mandrel quality is good then increment NewMand (counter for new mandrels that have been used in process), reset Uses to zero, and assign value of ManUses to new mandrel.]

IF Quality = 0
Uses = Uses + 1
ENDIF

[If mandrel quality is good then increment Uses (counter which tracks the number of times that the mandrel has been used).]

Quality = QualMP1 (1)

[Mandrel quality is assigned based on a random sample from the QualMP(1) distribution.]

Mandprep = Mandprep + 1

[Increment Mandprep (counter which indicates the number of mandrel preparation operations that have taken place on the part).]

IF Quality = 1
ScrapMP = ScrapMP + 1
ENDIF

[If mandrel quality is poor (1) then increment ScrapMP (mandrel prep scrap counter).]

IF Quality = 1 AND Liner = 1
CHANGE Mandrel to PrepMand
ENDIF

[If mandrel quality is poor (1) and a liner was used (1) then change the part name from Mandrel to PrepMand to reflect completion of the mandrel prep stage.]

The completed parts are routed to the next operation as follows:

IF Quality = 0
 PUSH to FW1Buff
 [If the mandrel is good then send it to the filament-winding buffer.]
ELSEIF Quality = 1 AND Liner = 1
 PUSH to MRBuff
 [If the mandrel is to be scrapped and uses a liner then it is sent to the Mandrel removal buffer.]
ELSEIF Quality = 1 AND Liner = 0
 PUSH to MandBuff
 [If the mandrel is to be scrapped and doesn't use a liner then the mandrel is sent to the mandrel buffer.]
ELSEIF Quality = 2 AND Liner = 1
 PUSH to MandRec
 [If the mandrel can be recycled and it uses a liner then it is sent to the Mandrel recycling buffer.]
ELSEIF Quality = 2 AND Liner = 0
 PUSH to MandRec
 [If the mandrel can be recycled and it doesn't use a liner then it is sent to the mandrel recycling buffer.]
ELSE
 Wait
 [Initiate no action until prompted by another operation.]
ENDIF

Many of the details of the machine are specific to the example being run at the time; however, the logic behind the actions and output rules can still be seen. The first eleven lines of the actions which are initiated upon completion of the mandrel preparation refer to mandrel usage. Each mandrel is assigned the number of times it will be used before being discarded. The first two lines use the attribute "ManUses" to assign this parameter to each of the new mandrels based on a distribution. During this specific example a negative exponential distribution was used with an average of 200. This distribution was used for testing to see whether the model performed properly when "Uses" was greater than "ManUses." The attribute "uses" is incremented each time the mandrel leaves the mandrel preparation step and the quality = 0 (good). This "uses" attribute is also compared to the "manuses" attribute. If it is larger and the quality =0 (good), the mandrel attribute "uses" reverts to 0 and a new value for "ManUses" is assigned. The number of times this occurs is tracked by incrementing the variable "NewMand" by one. Library files and explanations for the remaining submodels are provided in Appendix E.

At each process step a quality number is assigned to each part. During mandrel preparation each part is assigned a 0 for good, 1 for scrap, or a 2 for recycle (only mandrel preparation allows for recycle). This is based on a user defined quality distribution which is entered into the simulation. These quality value and the value of liner together determine the part's destination after leaving the process step and whether certain scrap values will be incremented. A value of "liner" equal to one indicates that either a liner is placed on a reusable mandrel or a one use mandrel exists which must be disassembled from the mandrel apparatus during the mandrel removal step. A value of zero indicates that the mandrel apparatus can be disassembled and reused immediately. If the part is good it continues to the next process step regardless of the value of "liner." If the part is considered scrap and has a liner, the part is sent to mandrel removal. The liner or mandrel materials are then disposed of during mandrel removal and the mandrel apparatus returns to the mandrel buffer. If no liner is used (i.e., liner=0) the reusable mandrel returns to the mandrel buffer where it will go to mandrel preparation again to be cleaned and sprayed with mold release. Any scrap materials are disposed of during mandrel preparation. If the part is being recycled it proceeds to the mandrel recycle buffer where it runs through another mandrel preparation cycle; however no new materials are added.

As was mentioned previously, materials are tracked using variables within the simulation. For example, in the mandrel preparation step the amount of mold release used is calculated by multiplying the amount of mold release used for each part times the number of mandrels leaving the buffer "MandBuff." The output streams for the mold release include the scrap amounts for all the process steps before mandrel removal and any mold release used for the mandrels removed during the mandrel removal step. Although the simulation tracks all necessary variables needed for inventory analysis, the output reports are required to do the analysis. The output report, for example, generates the amount of mold release used for parts which are scrapped after the mandrel removal step.

Output Report Implementation

The design and implementation of the databases and reports used for communicating information to the user was difficult because of the large number of equations which had to be developed and entered into the software. For this application, all databases and reports were developed using

Microsoft EXCEL. WITNESS creates a summary report that can easily be imported into EXCEL where further calculations can be performed. The report file for each WITNESS experiment was copied to the first sheet of the EXCEL workbook. The remaining output reports were each developed on another sheet within the same workbook. The equations developed for the output reports are provided in Appendix D.

The material report developed for this application includes numerical material balances for each of the materials used in the simulation. This information is generated using simulated data and information entered by the user. Implementing the material report required developing all the equations which calculated the quantity of each material type in each of the input and output streams. For the filament winding example 26 materials were tracked throughout the manufacturing process with 28 different input and output streams. This amounts to 728 calculations for the material report alone. In order to more easily design, update and verify the output report, many of the cells which contained the information needed for the material balance calculations were named. The cell name was then used in the calculations. Where possible the same names that were used in the simulation were also used in the output report. The equations used for the material report and all other reports are provided in Appendix D.

A list of all the important report definitions for the filament winding application are provided in Appendix F. Some of the subtleties of the definitions were not realized until the equations were developed and tested. Because of the amount of material in process at the end of the simulation run, the percentage of scrap and waste, for example, can be calculated by dividing the amount of scrap and waste by either the amount of material coming to the process or the amount of material leaving the process. In this case the "amount in" was chosen. Other important information which must be communicated to the user is what units are being used for each of the values. For the filament winding example the material database tracks all discrete parts, such as the parts assembled to the mandrel during mandrel preparation, by the number of individual parts. All processing materials are tracked by weight (i.e., pounds, kilograms). In the environmental and quality databases all materials are reported by weight.

Material balance information was used extensively to ensure all the equations were correct and were put into the appropriate cells. A summary of the material balance information is provided in Appendix G. The type of material, units, the materials database spreadsheet column, and the general equations that were used are included. The general equations include all the input and output streams and help identify which cells require equations for each of the materials. Because different equations are required depending on the order of submodels used in the individual simulation, logic statements were often required to determine which equation to use.

The material report was the most extensive and time consuming to create; however, environmental, quality, cost, and energy reports were also developed for this example. The environmental and quality reports include columns for lbs./finished part, lbs./week and cost/finished part for each of the pieces of information furnished. For the quality report, shown in Table 5.2.2, the scrap (poor quality) material is broken down by both type of material and processing step. This report includes all the material used in the production of poor quality products. It also includes all the parts disposed of during destructive testing in the batch inspection process.

The environmental report, shown in Table 5.2.3, lists the various waste types discarded by the manufacturing process and tracked by the simulation. This includes all discarded raw materials, materials in scrapped parts, materials discarded as waste during the cutting and machining operations, solvent bottoms and air emissions from solvent recycling, and discarded materials used for the production of good parts or work-in-process such as mold release, mandrels, and bag materials. Certain items such as laboratory wastes, drums and raw material containers, and rags and floormats used during the filament winding operation are not tracked by the simulation. The dust given off during machining and cutting operations is not tracked directly; however, the total amount of waste discarded during those operations is tracked.

Table 5.2.2 Example Quality Report

Quality Report	Wt/Finished Part	Wt/Week	Cost/Part
Process Scrap	Avg	Avg	
Mandrel Prep	1.39	38.22	$1.25
Fil Winding	0.67	18.42	$0.63
Cure	0.94	25.80	$0.88
Mandrel Removal	0.34	9.44	$0.32
Finishing	0.30	8.24	$0.28
Batch QI	1.99	54.60	$1.86
Ind QI	0.35	9.60	$0.33
Total	5.99	164.31	$5.56
Material Scrap			
Mold Release	0.43	11.90	$0.43
MP Adh Mat'ls	0.87	23.81	$0.87
Liner Mat'ls	0.87	23.81	$0.87
Mandrel Mat'ls	0.43	11.90	$0.43
Resin	0.29	7.92	$0.29
Fiber	0.29	7.92	$0.29
Additive1	0.29	7.92	$0.29
Additive2	0.29	7.92	$0.29
Cure Agent	0.29	7.92	$0.29
Prepreg	0.29	7.92	$0.29
Solvent-MP	0.14	3.79	$0.14
Solvent-1 FW	0.08	2.07	$0.08
Solvent-2 FW	0.01	0.15	$0.01
Solvent -MR	0.13	3.63	$0.13
Bag Mat'ls	0.00	0.00	$0.00
Assem Mat'l1	0.00	0.00	$0.00
Assem Mat'l2	0.00	0.00	$0.00
Parts-MP	1.30	35.71	$0.87
Parts-Assem	0.00	0.00	$0.00
Total	5.99	164.31	$5.56

Table 5.2.3 Example Environmental Report

Environmental Report	Wt/Finished part	Wt/Week	Cost/Finished part	
Waste Type	Avg	Avg	Avg	
Discarded RM's	0.98	18.04	$0.50	
Total Amount of Mat'l in Scrap	5.99	164.31	$5.56	
Machine Waste	0.00	0.00	$0.00	
Cuttings	0.00	0.00	$0.00	
Waste Resin	0.72	19.74	$0.72	
Solvent Bottoms	1.92	52.60	$1.92	
Air	2.40	65.71	$2.40	
Discarded Mat'ls used for good parts or WIP	2.58	70.62	$2.03	
Mandrel Mat'ls	1.00	27.52	$1.00	
Bag Mat'ls	0.42	11.54	$0.01	
Mold Release	1.00	27.52	$1.00	
Mandrels	0.15	4.04	$0.00	
Total	14.58	391.02	$13.12	
Environmental Categories	Waste/Finished Part	Waste/Week	Usage/Finished Part	Usage/Week
Ext Haz Sub-Rep Quantity	0.00	0.00	0.00	0.00
Ext Haz Sub-TPQ	0.00	0.00	0.00	0.00
Toxic Chemical	0.00	0.00	0.00	0.00
TRI Chemical	0.00	0.00	0.00	0.00
SARA H-1	0.34	9.23	11.15	305.68
SARA H-2	0.00	0.00	0.00	0.00
SARA P-3	0.00	0.00	0.00	0.00
SARA P-4	0.00	0.00	0.00	0.00
SARA P-5	0.00	0.00	0.00	0.00
Hazardous				
Non-hazardous				

The environmental report also calculates the quantity of materials used by environmental category based upon the environmental data section of the MSDS (Material Safety Data Sheet). Included are chemicals on the Toxic Release Inventory (TRI) list and chemicals in the various SARA categories. Knowing whether or not TRI chemicals are being used is important because EPA environmental regulations require certain reporting procedures for these substances. These categories were chosen because of their importance from a regulatory standpoint and because information pertaining to the categories can be easily found on the material's Material Safety

Data Sheet (MSDS). Other environmental categories (i.e., hazardous, nonhazardous, solid, liquid) were not included.

The cost report, shown in Table 5.2.4, breaks down direct costs into four categories: energy, materials, labor, and waste disposal. The material category is further broken down by type of material. The units are in both direct costs/finished part and direct costs/week. Quality and environmental costs were not specifically addressed in the cost report but can be found in the quality and environmental reports. The waste disposal costs must be calculated separately because of the difficulty in determining which wastes are hazardous and which are non-hazardous.

The energy report, shown in Table 5.2.5, breaks down the energy usage by machine. The report multiplies the user defined energy requirements per hour (KW) by the number of hours each machine is in operation to get a total energy usage (KW-hr) for the manufacturing period. The usage rates are displayed in both KW-hr/finished part and KW-hr/week.

All the reports generated for this research have used average values from WITNESS experiments that have run for a total of 8736 hours or one year of full time production (24 hours/day × 7 days/week × 52 weeks/year).

Verification of the reports and databases was also considered during their design. The amount of material coming into the manufacturing process and the amount of material leaving the manufacturing system were calculated as directly as possible so that the two values could be compared. A work-in-process value was also calculated which could be verified easily during testing. Since all material entering the process had to be either in-process, used for the production of good product, or disposed of as waste, the final amount of each material in these three categories was calculated as a percent. A total percent was also calculated and reported. If this number was not 100% it could easily be seen and corrected.

Table 5.2.4 Example Cost Report

Cost Report	Cost	Direct Costs/Part	Direct Costs/Week
Energy($/Kw)	$0.10	$21.45	$588.19
Materials($/lb or part)			
Mold Release	$1.00	$1.60	$44.04
MP Part1	$1.00	$1.59	$44.04
MP Part2	$1.00	$1.43	$39.63
MPAdhesive1	$1.00	$1.43	$39.63
MPAdhesive2	$1.00	$1.43	$39.63
Liner Mat'l1	$1.00	$1.59	$44.04
Liner Mat'l2	$1.00	$1.43	$39.63
Mandrel	$1.00	$0.03	$0.71
Mand Mat'l1	$1.00	$1.44	$39.63
Mand Mat'l2	$1.00	$0.00	$0.00
Resin	$1.00	$1.75	$48.26
Fiber1	$1.00	$1.58	$43.44
Fiber2	$1.00	$0.00	$0.00
Additive1	$1.00	$1.58	$43.44
Additive2	$1.00	$1.58	$43.44
Cure Agent	$1.00	$1.58	$43.44
Prepreg	$1.00	$1.29	$35.54
Solvent-MP	$1.00	$0.43	$11.89
Solvent1	$1.00	$8.61	$236.18
Solvent2	$1.00	$0.63	$17.31
Solvent MR	$1.00	$0.39	$10.63
Bag Mat'ls	$1.00	$0.03	$0.77
Assem Mat'l1	$1.00	$0.00	$0.00
Assem Mat'l2	$1.00	$0.00	$0.00
APart1	$1.00	$0.00	$0.00
APart2	$1.00	$0.00	$0.00
APart3	$1.00	$0.00	$0.00
APart4	$1.00	$0.00	$0.00
Labor ($/hour)			
General	$1.00	$73.51	$2,016.00
Maintenance	$1.00	$12.25	$336.00
Waste Disposal($/lb)			
Hazardous	$10.00		
Nonhazardous	$1.00		
Total Direct Costs		$138.65	$3,805.52

Table 5.2.5 Example Energy Report

Energy Report	Usage KW	KWhr/part	Avg KWhr/week
Mandrel Prep	10	61	1680
Filament Winding	10	35	949
Cure1	10	0	0
Cure3	10	0	0
Cure4	10	50	1380
Mandrel Removal	10	3	71
Machining	10	54	1475
Cutting	10	0	0
Assembly	10	0	0
Individual Inspection	10	10	280
Batch Inspection	10	2	47
Total		214	5882

Component Level Testing and Verification (Step 5.0)

Input Interface Testing and Verification

Because of the simplicity of the input analysis, the only testing performed was to ensure all data used during the verification and validation of the system was included in the question sets developed for the various process steps. The question sets were also reviewed with probable users to find out the appropriateness of the questions.

Submodel Testing and Verification

Each submodel was tested as it was designed and programmed into WITNESS. The submodels were developed in the typical manufacturing sequence. In the filament winding example, the mandrel preparation submodel was first, filament winding second, curing third and so forth. As each submodel was developed it was included in the simulation test model which, except for curing, consisted of all the submodels already in existence. During testing and verification, the simulation test model was run for approximately 1000 hours. Because there were four submodels which could be used for curing and only a maximum of two could be included in any manufacturing scenario, a choice was made to include only one curing submodel out of the four for this testing phase.

Output Report Testing and Verification

The initial verification and testing of the output reports and databases was performed by reviewing both the numerical data and the actual equations for correctness. Any data used for the reports which did not come from the simulation output file was entered as integers (i.e., 1). This made certain types of errors more visible. The "Total" value added to the material database was also checked for correctness. The quality and environmental reports had values which could be compared that also helped in initial verification of the model. For example, the total values for the "process scrap" and "material scrap" generated for the quality report could be compared. Because this verification was done with the output of only one simulation, no logic statements included in the equations could be verified properly during this stage of testing.

System Level Testing and Verification (Step 6.0)

Modular Simulation Testing

A limited amount of simulation testing had been performed on the model up to this point. During this phase, however, testing was performed to ensure that each of the submodels could interface with each other effectively for all possible manufacturing scenarios available to the user. Since testing each individual manufacturing scenario was considered unnecessary and too time consuming, it was decided to test the simulation utilizing experimental design concepts.

The first step was to decide which system variables could effect the proper functioning of the simulation. For the filament winding example, Table 5.2.6 lists the variables which were identified. The data which was to be monitored to identify any problems is also listed.

Table 5.2.6 Experimental Factors and Monitored Data

Major Factors	Minor Factors	Monitored Data
Placement of Submodels (Connections)	Batch Size	Part flow
Value of "Liner"	Number of Machines	Scrap Variables
Assignment of "Uses" and "ManUses" to Mandrels	Breakdowns (especially Filament Winding)	Solvent Variables
Assignment of "UsesB" and "BagUses" to Bags		Value of "NewMand" Value of "New Bags"

The placement of the submodels was the most complex part of the testing procedure. A list of experiments was developed which considered each process step and identified the different process step configurations. For the finishing operation this included every possible ordered sequence as shown in Table 5.2.7 in the finishing column. Each of the combinations was used as least once during the series of experiments. The set of ordered combinations developed for finishing would then be attached to the set of ordered combinations developed for the curing operation so that every possible submodel to submodel connection was applied at least once. For example, the submodel Cure4 was connected to each of the finishing operations (i.e., Machining, Assembly, and Cutting) at least once. The same process was used for the quality inspection process. The parts were also shipped from every submodel which was designed for that possibility. The completed list of 46 experiments can be found in Tables 5.2.7 and 5.2.8.

Table 5.2.7 List of Experiments for Simulation Testing for Option 1

Exp #	Mand Prep MP1	Fil Wind FW1	Cure/Precure C(1-4) Choose One	Mand Rem MR1	Postcure C(0-4) Choose One	Finishing F(0-3) Any Combo	Quality Insp QI(0-2) Any Combo
1	MP1	FW1	C1	MR1	0	-	-
2	MP1	FW1	C2	MR1	0	-	-
3	MP1	FW1	C3	MR1	0	-	B (MR1)
4	MP1	FW1	C3	MR1	0	-	IB
5	MP1	FW1	C4	MR1	0	MAC (MR1)	-
6	MP1	FW1	C4	MR1	0	CMA	-
7	MP1	FW1	C4	MR1	0	A	-
8	MP1	FW1	C1	MR1	C2	MCA (C2)	I (F2)
9	MP1	FW1	C1	MR1	C2	MCA	BI
10	MP1	FW1	C1	MR1	C2	AM	-
11	MP1	FW1	C1	MR1	C2	CA	-
12	MP1	FW1	C1	MR1	C3	-	-
13	MP1	FW1	C1	MR1	C4	-	B (C4)
14	MP1	FW1	C1	MR1	C4	-	IB
15	MP1	FW1	C2	MR1	C1	-	I (C1)
16	MP1	FW1	C2	MR1	C1	-	BI
17	MP1	FW1	C2	MR1	C3	AMC (C3)	-
18	MP1	FW1	C2	MR1	C3	CM	I (F1)
19	MP1	FW1	C2	MR1	C3	CM	IB
20	MP1	FW1	C2	MR1	C3	M	-
21	MP1	FW1	C2	MR1	C4	-	-
22	MP1	FW1	C3	MR1	C1	-	-
23	MP1	FW1	C3	MR1	C2	-	I (C2)
24	MP1	FW1	C3	MR1	C2	-	BI
25	MP1	FW1	C3	MR1	C4	ACM (C4)	-
26	MP1	FW1	C3	MR1	C4	MA	-
27	MP1	FW1	C3	MR1	C4	C	B (F3)
28	MP1	FW1	C3	MR1	C4	C	IB

29	MP1	FW1	C4	MR1	C1	CAM (C1)	-
30	MP1	FW1	C4	MR1	C1	MC	-
31	MP1	FW1	C4	MR1	C1	AC	-
32	MP1	FW1	C4	MR1	C2	-	-
33	MP1	FW1	C4	MR1	C3	-	I (C3)
34	MP1	FW1	C4	MR1	C3	-	BI

C1- Cure1 C3-Cure3 M-Machining C-Cutting B-Batch Inspection
C2- Cure2 C4-Cure4 A- Assembly I - Individual Inspection

Table 5.2.8 List of Experiments for Simulation Testing for Option 2

Exp#	Mand Prep MP1	Fil Wind FW1	Cure/Precure C(1-4) Choose One	Postcure C(0-4) Choose One	Finishing F(0-1)	Mand Rem MR1	Finishing F(0,2,3) Any Combo	Quality Insp QI(0-2) Any Combo
35	MP1	FW1	C1	C2	M	MR1	A	BI
36	MP1	FW1	C1	C3	M	MR1	C	IB
37	MP1	FW1	C1	C4	M	MR1	AC	-
38	MP1	FW1	C2	C1	M	MR1	CA	-
39	MP1	FW1	C2	C3	-	MR1	A	B
40	MP1	FW1	C2	C4	-	MR1	CA	IB
41	MP1	FW1	C3	C1	-	MR1	AC	BI
42	MP1	FW1	C3	C2	-	MR1	C	I
43	MP1	FW1	C3	C4	M	MR1	-	B
44	MP1	FW1	C4	C1	M	MR1	-	I
45	MP1	FW1	C4	C2	-	MR1	-	BI
46	MP1	FW1	C4	C3	-	MR1	-	IB

C1- Cure1 C3-Cure3 M-Machining C-Cutting B-Batch Inspection
C2- Cure2 C4-Cure4 A- Assembly I - Individual Inspection

The other factors which were investigated during this testing phase were nested into the original 46 experiments. For example, when submodel Cure4 was used, a mini experiment was conducted to see whether the variable "NewBags" was being incremented properly by changing the "BagUses" distribution and checking the outcome for reasonableness. Batch sizes and the number of machines were also changed during the experimental procedure to ensure no problems were encountered. Original values for cycle times, time between breakdowns, labor usage's, etc. were chosen based on one possible scenario.

For organizational purposes, a data collection sheet, shown in Figure 5.2.9, was designed to help collect and analyze the monitored data. The boxes were filled in with the process flow or submodels used for each experiment, the maximum being 10 individual submodels. Any important information concerning batch size, number of machines, "Liner" value, etc. was also

documented on the sheet. The process flow was input in the simulation test file and the simulation was run for 8,736 hours. The summary report for the simulation run was output to an EXCEL file and a printed copy was attached to the data collection sheet. Information from the summary report was transferred to the flow chart on the data collection sheet and checked to make sure the part flow was correct. All simulation variables were also checked for correctness. Any problems or corrective actions taken were also noted on the data collection sheet.

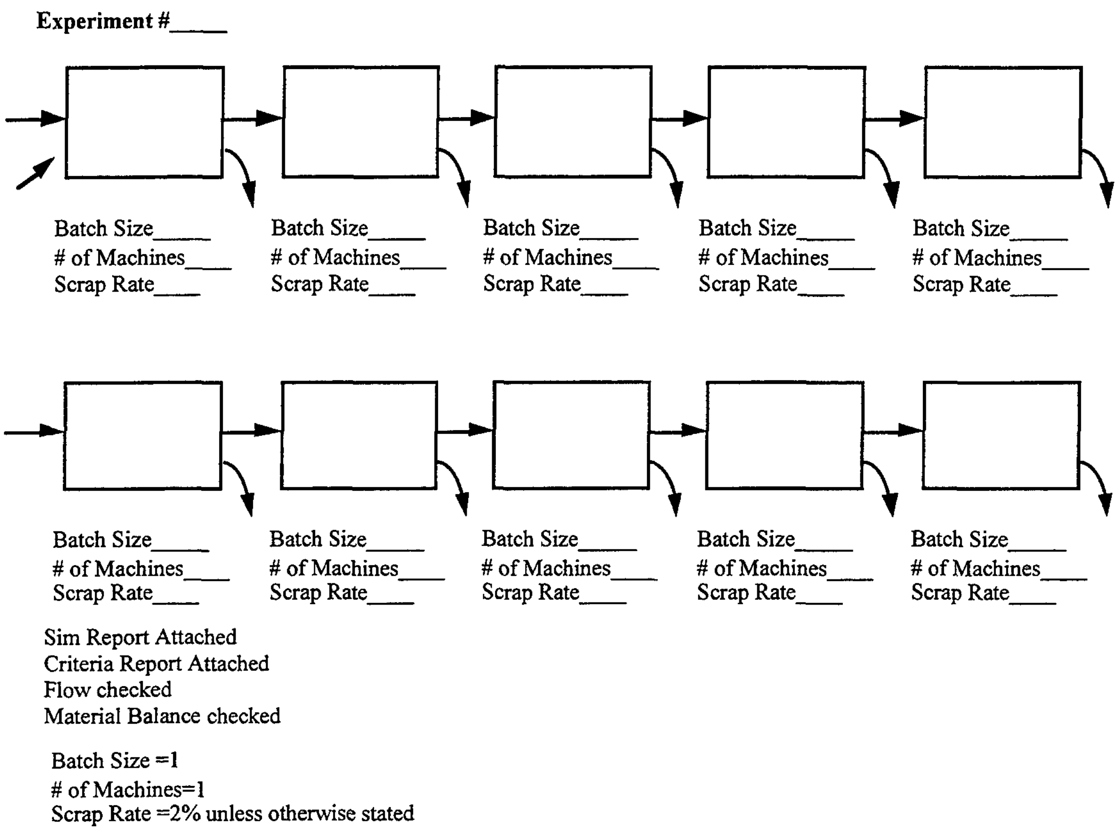


Figure 5.2.9 Data Collection Sheet for Reusable Simulation Testing

Modular Simulation and Output Report Testing

This step combined the simulation with the databases and output reporting elements of the system to ensure that these elements interacted correctly. In the filament winding example the main issues addressed, which effect the correctness of the output reports, were 1) the number and placement of the finishing submodels, 2) the number, type and placement of the curing submodels, and 3) the value of "Liner." A total of seventeen experiments were run. The data

collection sheet shown earlier in Figure 5.2.9 was used to record test results. Output reports and WITNESS reports were also included. The experiment number coincides with the experiment number from the previous testing.

Complete System Testing

Since this research does not include an automatic interface between the input and the other subsystems, the only testing performed using the input analysis was already complete. It was important that the questions be reviewed in conjunction with the simulation and output analysis to make sure all necessary questions were included and none were asked which no longer applied.

Validation (Step 7.0)

Validation entails ensuring that the simulation model does what it is intended to do. Validation is often difficult to perform because of the limited amount of data that may be available. Validation is also different with modular simulations because there are an infinite number of scenarios possible, and it is impossible to validate each one. For this application, a filament wound part currently being manufactured at the U.S. Army Aviation and Missile Command in Huntsville, Alabama was used as a test case to see how effectively the simulation system could be utilized. The part is currently produced in a laboratory on an "as needed" basis. Although there are no current plans to mass produce this part, data on current production methods was acquired to generate two possible manufacturing scenarios and compare them.

A description of the part and the current preparation procedures used in the validation example had been documented by the U.S. Army. The part is used to determine whether or not certain methods of pressure testing missile motor cases could damage and harm their structural integrity. The description and procedures are given below:

A testing apparatus was to be constructed before the actual proof testing could begin. This apparatus is the AMCOM 3.00-inch pressure vessel, otherwise known as a 3.00-inch "bottle" because of its shape. The bottle is a filament wound graphite/epoxy enclosed cylinder with a

length of approximately 12.5 inches and a diameter of 3.00 inches. This design was chosen because it most closely represents the shape and structure of a missile motor case.

Steel molds are used to form the sand mandrel over which the graphite fibers will be wound. The molds are first prepared by coating the insides with Teflon tape. After assembly, a combination of dry sand and sodium silicate is prepared to be packed into the molds. One cup of the mixture consists of 335.7 grams of sand and 26.9 grams of sodium silicate. Four cups are needed to fill one mold. After one cup is mixed and placed into the mold, a nylon rod is used to pack the sand. This procedure is repeated 3 more times until the mold is filled completely. An aluminum plunger is used to close off the mold and approximately 5 tons of pressure is added to completely compact the mold. The molds are then placed in a 220 degree oven overnight. After cooling, the molds are disassembled and the finished sand mandrel is removed.

Once the sand mandrel is completed, it can now be assembled for winding. First aluminum pole pieces are grit blasted and placed on each end of the sand mandrel. The mandrel and pole pieces are then secured onto an aluminum arbor which allows the mandrel to be attached to the machine parts for winding. Next, the entire arbor with sand mandrel and pole pieces is placed into a 170 degree oven for one hour. A piece of 10 inch long heat shrink tubing is arranged evenly over the mandrel and then put into a 250 degree oven in order to shrink the tube over the mandrel. This shrink tubing will act as a barrier between the fibers and the sand mandrel and act as a bladder during testing.

A mixture of 7.7 grams of Epon 826 (epoxy resin), 2.3 grams of Kelpoxy g-293 (rubber modifier), and 18.0 grams of Versamid-140 (elastomer and accelerator) is formed to provide a closure at the point where the shrink tubing meets the pole pieces. Known commonly as flexible amide or flexible rubber, this substance of low viscosity is easily applied to the bottle and then hardens after curing.

The bottle is now completely ready to be filament wound. A graphite fiber, IM-6 was chosen for the wrap because of its high strength and durability. An epoxy resin is combined consisting of the following ingredients:

(1) 200 grams -- 826
(2) 20 grams -- RD2 (a diluent which lowers the viscosity)
(3) 180 grams -- 906 (or nadic methyl anhydride hardener)
(4) 3 grams -- EMI-24 (the curing agent)

The resin will provide the matrix for the bottles once hardened by curing. This will keep the fibers in place, provide all the interlaminar shear strength for the bottles, and protect the bottles from cracking.

The graphite fibers are wrapped three times over the mandrel in two different patterns in what is called the XXO pattern. X represents one helical layer wound at a 30 degree angle, and O represents the outer hoop layer wound at 90 degrees.

After winding, the bottles are "wet" from the resin and must be cured to activate the hardening elements. A cure cycle of 24 hours is required consisting of the following stages.

(1) overnight at 140 degrees
(2) begin ramping to 160 degrees in the morning
(3) increment by 20 degrees every hour until temperature reaches 300 degrees
(4) leave at 300 degrees for 3 hours.

After the part is cured it is ready for pressure testing.
By utilizing these procedures and the flow diagrams and question sets provided in Appendix A, enough information was acquired from U.S. Army personnel to begin the example problem. Since the purpose of the simulation is to compare composite manufacturing options for a similar part based on multiple criteria, this type of analysis was to be performed for the example part. After reviewing the manufacturing procedures used in the laboratory it was decided that many of those procedures could be carried over to a mass production environment. However, in the laboratory it took approximately three days to produce four sand mandrels. This was considered to be inefficient enough to consider other options for mandrel preparation. For the example problem, two different mandrel options were analyzed using the simulation. The first analysis was performed for a process which used premade sand mandrels which had to be prepared by attaching the aluminum pole pieces and shrink tubing. These were sent to the filament winding

operation and then to curing. The curing process was performed in a batch oven which could hold 10 parts but had no buffer capacity. The reason for zero buffer capacity is that the parts coming off the winder are in an uncured state and must be continually rotated so that resin does not gravitate toward the bottom of the part. These rotation devices were in the oven only. The last step was mandrel removal. Because of the type of mandrel being used, the mandrel materials were flushed out using water and then discarded.

The second option to be analyzed was a process which used reusable steel mandrels which could be disassembled and removed from the part. Because of the different mandrels, changes to both the mandrel preparation step and mandrel removal step had to be considered. The filament winding and curing operations were to be identical to those in the first option. A comparison of the simulations can be found in Table 5.2.9.

Table 5.2.9 Comparison of Inputs for Option 1 and Option 2

Differences	Option 1	Option 2
Mandrel Preparation 2-1		
Question Set Used	2-2	2-1
Mandrel Type	Pre-made Sand Mandrel	Reusable Steel Mandrel
Cleaner	None	Acetone
Mold Release	None	Teflon
Scrap Rate	5%	2%
Mandrel Removal 2-1		
Question Set Used	5-2	5-1
Solvent Used	Water	None
Cycle Time	Triangle(0.75,1,1.5) hr	Triangle (0.2,0.25,1.0) hr
Scrap Rate	2%	0.5%

After a preliminary review of the two manufacturing options, which included developing flow diagrams, all appropriate question sets were filled out for each option. The flow diagrams are shown in Figures 5.2.10 and 5.2.11. Both diagrams show the four processing

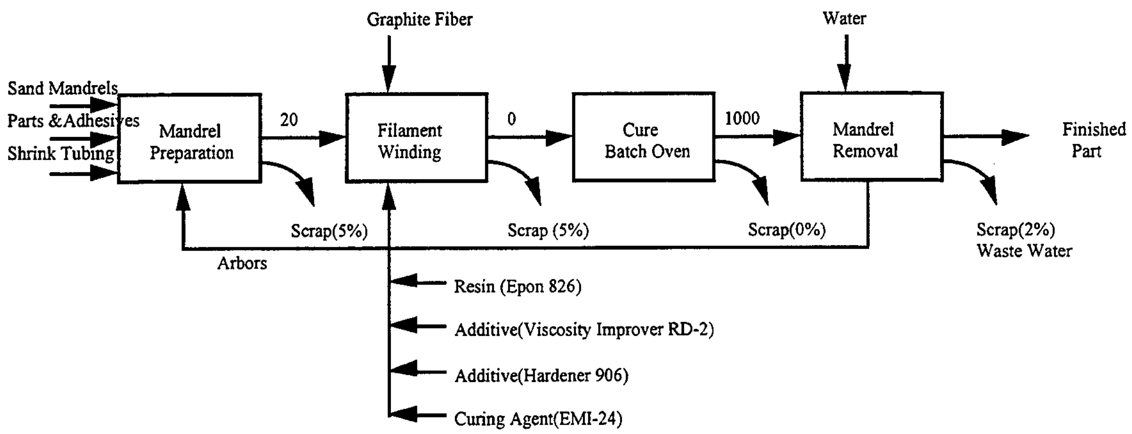


Figure 5.2.10 Flow Diagram for Manufacturing Option 1

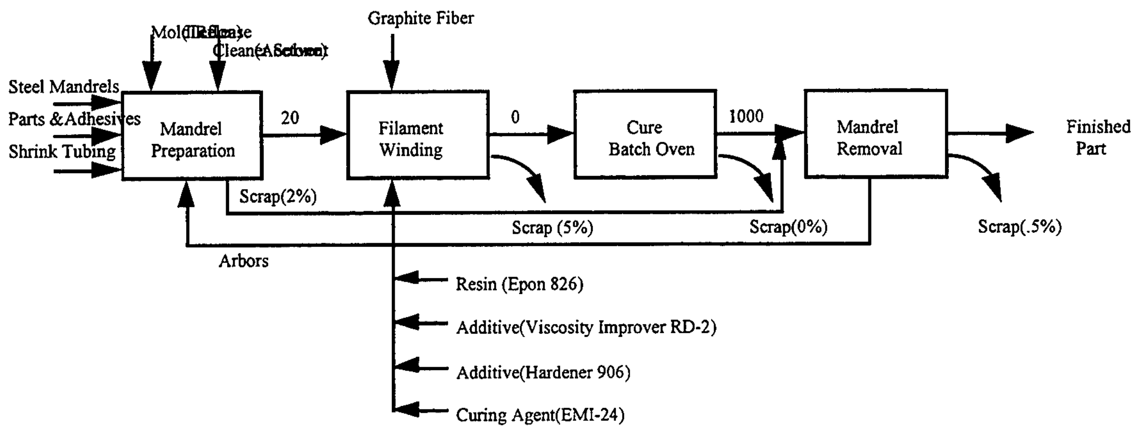


Figure 5.2.11 Flow Diagram for Manufacturing Option 2

steps used for the manufacture of the pressure vessels. The two diagrams are very similar and differ only in that 1) the materials used for mandrel preparation and mandrel removal are different and 2) the scrap rates are higher for Option 1. Each simulation was run for a total of 8,736 hours. The reports for both options were generated and are provided in Appendix H.

After the reports were generated, the results from both manufacturing options were compared to see if using reusable steel mandrels would offer results which would make additional inquiry worth pursuing. Table 5.2.10 shows the output values of key criteria for both options. From the table is can be seen that neither option is the clear choice. Option 1 has much higher total waste

(g/part) than Option 2. However, this is primarily due to the waste water used to remove the sand mandrel from inside the finished part. The cost of waste and the

Table 5.2.10 Comparison of Key Performance Criteria for Option 1 and Option 2

Key Performance Criteria	Option 1	Option 2
Environmental		
Total Waste (g/part)	21327 grams	212 grams
Total Waste ($/part)	$21.20	$20.19
TRI chemical usage (g/part)	59.81 grams	58.98 grams
Quality		
Process Scrap (g/part)	2462.57	50.22
Process Scrap($/part)	$11.50	$9.43
Cost		
Total Direct Costs($/week)	$6,481	$6,785
Total Direct Costs($/part)	$129.68	$134.00
Energy		
Total Usage(KWhr/part)	35 Kwhr	34 KWhr
Total Usage(KWhr/week)	1722 KWhr	1723 KWhr
Process		
Yearly Capacity	2582 parts	2622 parts

TRI chemical usage is equivalent for both options. The cost of producing poor quality products is higher for option 1; however, total direct cost to produce a part is higher for option 2. Energy usage is essentially the same for both options. Capacity or yearly output is slightly higher for Option 2.

Depending on the importance that the user might place upon certain criteria, one option may appear slightly better than the other. Other issues such as how many of these parts will eventually be produced may also change the picture slightly because the reusable mandrels can still be used for quite some time without being replaced and incurring any additional costs. If significant costs would be incurred to design the reusable mandrel, that may also be considered in the decision as to which option should be used. It can be seen however, that the reports generate a significant amount of information with which to compare manufacturing options as well as look for ways to improve the options already analyzed.

Using the Simulation

This modular multi-criteria discrete event simulation was designed to be used in conjunction with life cycle design. The strategies and tools associated with life cycle design were discussed in Chapter II. Because this simulation model is limited to the manufacturing phase of the product life cycle, the effect of implementing the strategies can be directly measured for only four of the strategies; material life extension, material selection, process management, and reduced material intensiveness. Table 5.2.11 shows the life cycle design strategies which can and cannot be directly employed using the simulation model. An overview of each strategy, a discussion of how a modular simulation system will aid the engineer in implementing the strategy, possible limitations of the modular simulation, and an example from the filament winding case study have been included in this section.

Material life extension deals primarily with recycling. The recycling can be performed on both a pre-consumer or post-consumer basis. Since most materials are currently not being recycled on a post consumer basis and often have many obstacles to overcome

Table 5.2.11 Life Cycle Design Strategies

Strategies Not Directly Employable	Employable Strategies
Product Life Extension	Material Life Extension
Efficient Distribution	Material Selection (In Process)
	Process Management
Improved Management Practices	Reduced Material Intensiveness

before becoming reality, the primary focus for most simulations will be on preconsumer closed-loop recycling. If the simulation system is designed to model pre-consumer closed loop recycling, the effects on raw-material usage and throughput can be determined.

The selection of the materials used during the fabrication process is another critical strategy used not only in environmental impact reduction but in product and process performance. The effects

of changing a material can be complex and far-reaching. For example, a change in material may reduce the amount of toxic materials being discarded, while at the same time increase the processing time of one or more steps, and increase the amount of scrap and rework. The simulation model should aid the user in viewing the overall impact of material selection on a number of performance parameters and reduce the chances of myopic vision on the part of the design engineer.

Another strategy that can be employed is process management. Process management includes process substitution and modification of the process to reduce the amount of materials and/or energy utilized. Process control, process layout, inventory control, and material handling are all aspects of process management. Just as in material selection, the process utilized to manufacture products has far reaching effects on almost all performance parameters, including product performance, quality, and cost. The effects of certain aspects of process management can be estimated through the use of this simulation model. Depending on the various modular simulations available to the user, the effects of modifying a particular type of manufacturing process as well as changing the type of manufacturing processes (i.e., filament winding vs. pultrusion) can be estimated. The energy and material usage for the machines can also be varied. The effects of some process control and inventory control issues may not be able to be estimated directly from the simulation. These include such things as the temperature of the oven, winding speed, or saw speed. These effects can be indirectly estimated by determining their effects on certain parameters which the simulation can handle (i.e., quality of product or processing times) and inputting those parameters. Determining these effects can be done either theoretically or by laboratory testing.

Reduced material intensiveness is another strategy which deals with the materials used during fabrication. Rather than substituting raw materials, this strategy reduces the amount of the same raw material used. Sometimes this may work effectively and is an excellent way of reducing environmental impact. There may be other side-effects which must also be considered when implementing this strategy. As in the process management strategy, the simulation will not be able to estimate the side effects of reducing raw material usage directly and input them into the

simulation. However, if the effects are estimated beforehand and parameters are input which the simulation can handle, a better idea of the overall impact of the strategy can be ascertained.

The fifth strategy which can be used to reduce environmental impact is product system life extension. This strategy focuses on making the initial product more reliable, durable, maintainable, etc. so that fewer products will have to be made in order to meet a given need. Simulations of this type can be used for this strategy if simulations are available for both manufacturing processes. For example, oftentimes a metal part is being compared to a composite part for the same end use. In this case, a simulation may give important information on manufacturing parameters of the composite part but the user would have to estimate the manufacturing parameters of the metal part by some other method. Adjustments would have to be made by the user to determine life cycle effects based on the number of products required, since that will differ.

The last two strategies given in the life cycle design manual include efficient distribution and improved management practices. Efficient distribution strategies deal with the packaging and transportation of the product. Improving management practices refers to administrative and business procedures. Since the modular simulation developed in this dissertation models the manufacturing process only, it does not help in the implementation of these strategies. Many of the concepts used in the methodology to design and build the modular simulation system could, however, be used to develop modular simulations for other processes within the life cycle of a product.

Life cycle design also includes utilizing a number of tools to assess the environmental impact of a particular product. Inventory Analysis, which consists of identifying the materials throughout the manufacturing process and quantifying those inputs and outputs, is one of these tools. A general inventory analysis or material balance is essential both for life cycle design and for developing a modular simulation model. For each simulation a general inventory analysis must be performed. This includes raw materials, waste products, and energy usage. The general inventory analysis is used as a framework to develop the simulation system, including the questions asked of the user, which submodels are needed, and the reporting format.

One of the problems associated with inventory analysis is the lack of data or the high cost of obtaining it. Because of the importance of inventory analysis data to the life cycle design process, some system must be put in place to gather the needed information. For the filament winding case study the user is asked to supply information on how much material is used for the product, what percentage of certain materials are disposed of during given manufacturing steps, and what percentage is recycled or disposed of as particular type of waste. If any chemical on the Toxic Release Inventory (TRI) list is utilized the amount of those materials released into the environment must be estimated. Also, because of the Resource Conservation and Recover Act (RCRA), most companies will have to obtain at least some estimate of the waste being generated. In 1987, the EPA provided four general methods that could be used to estimate releases subject to Toxics Release Inventory reporting which may also be helpful in determining general inventory information [Tracking Toxic Substances at Industrial Facilities, 1990]:

> 1) Calculation based on measured concentrations of the chemical in a waste stream and the volumetric flow rate of that stream.
>
> 2) Mass balance around entire processes or pieces of process equipment. If input and output (i.e., product) streams are known (based on measured values), a waste stream can be calculated as the difference between the input and product (accounting for accumulation or depletion of the chemical in the equipment).
>
> 3) Emission factors, which usually express release as a ratio of amount released to the amount of chemical flowing through the process. (Release estimates are obtained by multiplying the emission factor by the amount of chemical flowing through the process for which estimates are needed.) Emission factors, which are commonly used for air emissions, are based on the average measured emissions at several facilities in the same industry.
>
> 4) Engineering calculations and/or judgment based on physical and chemical properties and relationships, such as the ideal gas law.

Based on the information entered by the user, the simulation will be able to perform mass balances on the materials (Material In - Material Out (finished product + waste) = Material In Process) and give a much broader view of the way materials flow through the process.

Impact Assessment is another tool used in life cycle assessment. Based on inventory data the overall impact to the environment is measured. Included in this assessment are resource depletion, ecological degradation, human health effects, and other human welfare effects. This simulation model will improve impact assessment because the information output will include the amount of materials used and amount of different types of waste generated. The environmental reporting structure of the modular simulation system can be as detailed as time and money allow. Environmental databases could be set up that search for OSHA information, Sara Title III requirements, and Class I and II substances for the materials used. Complex artificial intelligent systems could be used to categorize the waste streams into the various waste categories. All these ideas would help even more in determining the overall environmental and health issues. Some European countries have created indexes such as the Green Index which prioritize and weight certain environmental effects into one number.

Life cycle accounting, another tool used in life cycle design, attempts to more accurately measure the total costs associated with producing, distributing, using, and disposing of a product. In order to do this, hidden and less tangible costs should be taken into consideration. Although this simulation tool does not attempt to estimate all the hidden costs associated with a product, because of the nature of simulation it does help advance the use of life cycle accounting in two ways. First, because accounting can be done very quickly and accurately using simulation, life cycle strategies can be tried and their costs measured much more efficiently than with traditional techniques. For example, if a certain waste minimization strategy is being considered and it is known to reduce solvent usage by 30% but increase cleaning time by 10% and increase the number of scrapped parts by 1-2%, this information can be easily input into the simulation and a broad overall cost impact of the strategy can be estimated within minutes. The second way in which the simulation advances life cycle accounting is by more effectively measuring costs associated with environmental impact and quality. These simulation models can be used to output the total cost of materials discarded as waste. They can also generate material costs associated with producing poor quality product. If the information is reported "per good part produced" it also includes changes in the production of usable product that may have also occurred.

5.3 Static analysis

Often it is desirable to have a quick look at the potential production capabilities of a manufacturing line. Certainly a complete simulation of the line can give great detail, but often the information or the time required to produce the complete simulation is unavailable. A static analysis provides a statistical average view of the production at each element within the process flow model. It is termed "Static" because all of the variability of the simulation parameters has been removed. Therefore the analysis appears in a constant or static state. The technique averages the production cycle time, breakdown, and repair time parameters and uses them in a series of maximum throughput calculations. For a single manufacturing line that has only one of any of the process elements in the production line, the rate calculations are

$\text{Rate}_i = (\text{time period} / (\text{production cycle time})_i)$ and
$\text{Effective Rate}_i = \text{Rate}_i * \%\text{Operation} = \text{Rate}_i * (1 - (\text{Repair Time})_i / (\text{Time Between Failures})_i)$.

Now the throughput rate for the entire manufacturing line can be found by finding the minimum effective rate for all elements. Therefore, the production limit for the manufacturing line is defined as

$\text{Production Limit} = \text{Min}_i\,(\text{Effective Rate})$.

The bottleneck location for the production line can then easily be identified by as the element in the process flow where the effective rate equals the production limit. This gives the manufacturing engineer information that may allow him to better design the process flow or add additional elements to increase production.

5.4 Team communication

The DTAME Communication Facility is a World Wide Wed based application that allows user to work together while authoring a group document on the world wide web.

Features of the Communicator include:

User access

Only authorized users may access the project, and only users assigned to a certain section of the project can submit to or update that part of the project.

Web-Based File Submission

Project components can be submitted via the world wide web using a HTML 3.2 compliant browser. There is no need for ftp or telnet.

Configuration Management

The project administrator may change global configurations and document form, and individual users may change the configuration of those sections for which they are responsible.

Portability

The source code for the communicator should be portable to any UNIX platform that supports Apache, Postgres95, the Bourne Shell, GCC (or any reasonably ANSI C compiler) and AWK.

Implementation

The DTAME Communication Facility is a composed of several key components.

Apache.

A "patched" version of the NCSA http daemon, Apache is a free hypertext server produced by the Apache Server Project. It is portable, fast, and very flexible.

Postgres95

Implementing an subset of SQL, Postgres95 is the database server that allows the DTAME Communication Facility to track project entries and changes. Originally created by the Database Research Group at UC Berkeley, Postgres95 is now being maintained by volunteers and is available from www.postgresql.org.

Installer

The Installer is a C-language program that initializes the database structures and creates the hypertext directory tree.

CGI scripts and SSI documents

The bulk of the work of interacting w/ the user is performed by CGI (Common Gateway Interface) scripts and SSI (Server Side Include) documents. In both cases, these are a techniques of persuading the httpd to execute programs to generate data for use in hypertext documents , or to process the input form a user form. These programs and scripts are written using C, AWK, the Bourne Shell and the Postgres95 API. Browsers the government approves for export are very weak on encryption. Several Netscape-based

encryption sessions have been broken by a co-operative effort on the net in times ranging from weeks to a few days. Browsers not available for export (i.e. obtained form outside the U.S., obtained directly from the vendor, or patched yourself) can support SSL and key lengths (say 128 bits as compared to 40 bits for export) that provide very good security.

The DTAME Communication Facility is designed to be intuitive, but an overview may be helpful..

Startup

To begin your session, simply access the url of your project. You will be prompted for your username and password, just type your the values as normal.

Main Page

The main page shows an online of your project with links to portions submitted, a list of project members with names and a short comment, and links to the submission log, your personal directory, and this help file.

Submission log

This is a simple list of all materials that have ever been submitted to the project.

Home Directory

In the home directory there are 3 icons...

Submit a section

The Submit Section button takes the user to a page where you are asked to attach a file to a location in the project.

Change outline structure

This button takes you to a menu where the user may make changes to portions of the project over which she or he have control.

Change user attributes

This button takes you to a page where the user can change her or his password, full name, or plan. If the user is also the administrator, she or he can change other users values also.

5.5 Simulation Optimization

Simulation optimization using genetic algorithms was demonstrated with two prototype systems. One system, a small assembly line, was studied in order to gain understanding of the Witness interface. The second system, a 10 machine processing line serves as the initial case study for the applicability of genetic algorithms (GA) as optimizers of simulation models. A detailed report documenting the results of this study is provided in Appendix I.

The simulation model was first created and then it served as input to the genetic search procedure. First the members of the population were generated from the primitive model. These include variations of process parameters: cycle time, conveyor length (buffer size), and number of machines. Each such variation results in a new member of the population. The population can be viewed as the set of all possible system configurations.

The genetic search procedure operates on this population, producing offspring that are evaluated according to a fitness, or evaluation, function. This fitness function takes into account cost, average work in process and average flow time in the system. The optimal solution from each generation was then simulated to provide a more detailed evaluation.

Thus we have a two-step procedure for evaluation:

1)use a genetic search technique to find the optimal system configuration for a particular generation, and

2)simulate the "winners" of each generation

This evaluation continues until a predetermined stopping rule is invoked. This two-step procedure reduces the number of simulation runs required. Traditionally, design of experiments and Taguchi methods have been used to determine the number and variations of runs required. We are attempting to reduce this process by pruning with genetic algorithms so we only simulate the best candidates.

From this initial work it is clear the GA is potentially an effective search method for optimizing the parameters associated with a manufacturing line. In both lines studied, the GA outperformed both an intuitive approach and a random search routine. There are still a number of questions to be answered. These questions include:

- Is there another search method (such as a derivative search) that is more effective than the GA?
- If the GA is run for more generations, is a better solution obtained?
- How well will the GA optimization approach work when the size and complexity of the lines are increased?
- Will the GA optimization approach be able to effectively handle multiple optimization objectives?

5.6 Integration and User Interfaces

Although each of the DTAME software components have their own user interface, a prototype system interface has been developed that allows the user to interface with the various software packages. The interface represents a generic view of the system and allows the user to create a single input model for all of the system components. This should provide the user with several advantages over using each of the individual interfaces. Some of these advantages such as the ease and uniformity of data entry, model reusability, sub-component operational knowledge requirements, and centralized output analysis are discussed in the following sections. The user still has the option to modify information within the individual software elements as desired, however for reasons described below, this is not advised.

The interface is designed in a manner to facilitate the entry of information into the DTAME system. This is accomplished by providing the user with a set of specially designed input screens and menu selections that are tailored for the manufacturing process being evaluated. After making a few simple selections from an opening screen, the user is guided through a set of questions and answers to arrive at a final model configuration. The interface is constructed using specifically grouped screens of drop down selections, radio selection boxes, BOOLEAN check boxes, and simple type-in areas. A more detailed description of the working interface is provided later.

Obviously the rapid development and reusability of the model will speed up evaluation time since the same data is not required to be redundantly entered into each of the software packages. Data is entered once and then automatically supplied to the software when the user selects which type of analysis is desired. While a familiarity with each of the individual software components is recommended, the user only needs to be able to use the centralized input features to create and analyze the model. This feature alone makes the concept of a single centralized interface attractive.

By using a common input module, the consistency of the data is maintained across each of the analysis components. Any change made to the model would be reflected in the sub-components analysis automatically when new evaluations were made. This feature relieves the user from task of remembering to include the modifications or locating the appropriate location of the modification in each of the component software packages.

The metric model, simulation package, and static analysis all have different, yet similar, input requirements. They also have different input mechanisms and styles. Manufacturing parameters and process flow rules are defined differently. And program initiation, execution, and output presentation differ. The interface attempts to reduce these issues by automatically loading the model definition information into the various software programs, executing the programs, and extracting the information for the user. This means that while familiarity with each software package is a definite plus, you do not have to be an expert in the use of the software to benefit. A simulation run or static analysis of the model now becomes a menu option. The selection is executed and the results presented to the user.

The interface now becomes the central analysis tool since the output information from each of the system's component packages can be directly accessed. Tables, charts, and any summary calculations of the data can be performed and presented. The information can be presented as individual analyses or combined. Therefore by simultaneously presenting the results from the different analyses the interface assists in giving a better over-all view of the model performance.

At least this is the eventual interface goal. The prototype currently provides links to two of the four elements of the system, the Witness model and the Static Analysis. This interface is presented in Appendix J. Both input and output links are in place for these two system component packages. Further development is underway to extend the interface capabilities to include the remaining software components of the DTAME system.

6.0 Application activities: CAV

6.1 Application Activities: Composite Armored Vehicle (CAV)

The Composite Armored Vehicle is an Advanced Technology Demonstrator developed for the U. S. Army Tank and Armament Command (TACOM). The results from the development of the CAV/ATD are to be applied to future armored vehicles such as Crusader.

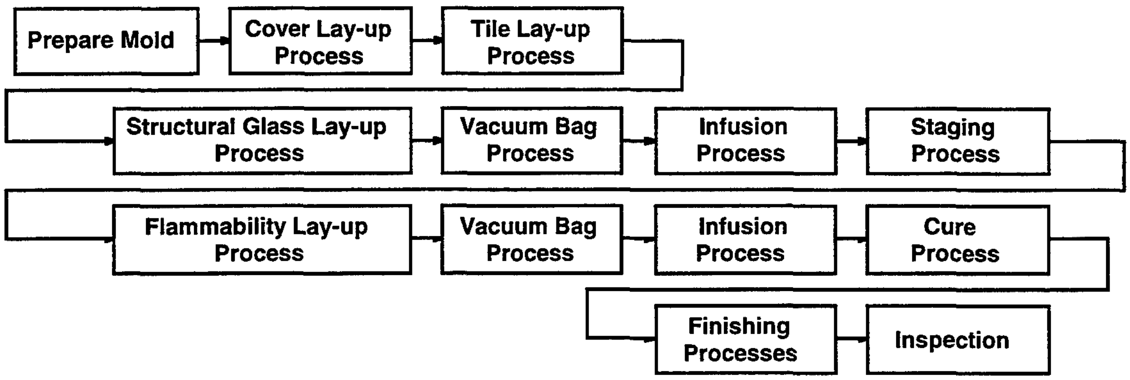
Goal of this effort was proof of concept and demonstration of the DTAME simulation capabilities for projects similar to CAV. The prototype simulation system was to include the capability to model Vacuum Assisted Resin Transfer Molding (VARTM) and the Automated Fiber Placement (AFP) processes. The prototype system consists of three basic parts: a Visual Basic™ front-end used to describe the basic manufacturing system and input of the processing parameters; a Witness™ model of the candidate processing system; and an output display generator for displaying graphical and textural information of the simulation results.

6.2 Technical Interchange Meeting

A technical interchange meeting was held on 9 September 1997 at the U. S. Army Aberdeen Proving Ground. Participants included: Mark Bower and Phillip Farrington (UAH), George Thomas, (UDLP, San Jose), Luis Hinojosa (TACOM), and Ray Harrell Dan Holder, and Anthony Howard (AMCOM).

The participants reviewed the VARTM process used by UDLP for CAV. From this review they identified the basic structure of the simulation model for the CAV VARTM process. The

simulation system will be developed using data provided by UDLP for three CAV parts: sponson/sidewall, skirts, and upper hull. The parts were selected based on the differences in their relative complexity. The UDLP VARTM process is shown below.



The flow diagram illustrates thirteen major steps in the manufacturing process. Significant in the process is that there are four independent lay-up processes that may or may not be present for a particular VARTM part in CAV.

7.0 Future directions

7.1 Simulation

One purpose of the research relating to the development of the simulation modules was to develop a methodology which uniquely integrates environmental, cost, quality, and production criteria into a modular simulation system for a given manufacturing domain. The modular simulation system obtains relevant information from the design engineer, efficiently models a variety of manufacturing options for the given manufacturing technology, and generates quality, environmental, cost, and production reports for use by the design engineer when considering manufacturing alternatives. The developed methodology was the basis for a prototype modular simulation system for the filament winding composite manufacturing technology application.

Life cycle design and waste minimization concepts point out the importance of this research as it relates to 1) understanding and reducing the environmental impacts involved with manufacturing

a product, 2) incorporating environmental criteria into design decisions, and 3) considering environmental impact together with other criteria such as quality, cost, and processing. Although simulation has been used for many years in the area of manufacturing design, advancements in simulation software have led to the design of user-oriented modular simulation packages which offer opportunities for developing simulation systems tailored to particular needs. The integration of life cycle design techniques, modular simulation software, and artificial intelligence techniques offer an opportunity to develop a new type of simulation system which can be used to efficiently evaluate various manufacturing design alternatives for a given domain utilizing a system of requirements (i.e., quality, environmental, production, cost). Although much work has been done in the area of life cycle design, modular simulation, and composite manufacturing, no published work could be found on designing and applying modular simulation models to multi-criteria manufacturing design issues. The tools currently available for life cycle design and waste minimization analysis are manual and analytical in nature and make it difficult for engineers to look at design requirements from a systems engineering viewpoint.

This research presents a methodology which can be used to design domain specific modular multi-criteria discrete-event simulation systems. These simulation systems include three subsystems: 1) the input subsystem which obtains relevant information from the user to develop simulation models of possible manufacturing alternatives, populate the individual submodels being utilized, and calculate individual parameters for the output reports, 2) the simulation subsystem which acts as the simulation engine and also stores the submodels which are utilized for the development of the individual simulation models, and 3) the output analysis subsystem where information from the simulation and the user is combined to produce quality, environmental, cost, and production reports.

Although modular simulation software has been available for a number of years, embedding manufacturing domain knowledge into an expert system-like front end and integrating environmental, quality, and cost criteria into the simulation makes this research unique. One of the primary challenges associated with this research is the tracking of the various materials throughout the system. Because of the reusability aspect, many different combinations of process steps are possible. The ordering of these process steps affects the composition of the input and

output streams, which in turn affect the material balance. Because of the complexities of keeping track of each material for each of the possible manufacturing scenarios and creating an input system which aids the user in determining the manufacturing options available, considerable time must be spent on understanding and documenting the overall manufacturing technology being simulated. This methodology includes tools and techniques which can be used to document important manufacturing domain knowledge which is then utilized to design the input question sets, simulation submodels, and output reports.

The methodology has currently been applied to the design and development of a modular multi-criteria simulation system used for modeling filament winding manufacturing systems and a subset has been applied to a vacuum assisted resin transfer molding process. An analysis of filament winding fabrication methods was conducted to obtain important manufacturing and environmental knowledge needed for the development of the simulation system. The filament winding simulation system included 1) all questions and databases needed for the input subsystem, 2) a modular simulation model which included twelve different submodels representing six process steps, and 3) material, quality, environmental, cost, energy, and production report capability. Validation of the filament winding example was completed using an example from the U.S. Army Aviation and Missile Command at Redstone Arsenal, Alabama. Two manufacturing options which produced test pressure vessels were compared utilizing the simulation system. The example illustrated that the system could be utilized successfully for real world applications.

This research has shown the feasibility of designing a modular simulation which can be used during the design phase to provide estimates for quality, cost, environmental, and processing parameters. The filament winding application is only one example of what could be accomplished with this technology. In the example, the majority of effort was spent on modeling the basic manufacturing process steps. Although this is the basis from which modular simulations of this type should begin, they can be expanded and improved in many ways. If the system was expanded, production and manufacturing engineers could also use it to model existing manufacturing facilities and evaluate the impact of improvements on the various output

parameters. While the application is complete, there are still several possible improvements which will be discussed in the following paragraphs.

First, the system should be made as user-oriented as possible. Currently, the filament winding example does what it set out to do. However, all input data must be manually entered into the appropriate database or the simulation. An automated user interface is essential for wide-spread use of the system. This interface is currently in the development phase. Some aspects that could be included are automatic conversion of units, a printout of all user input for easy verification, and a help menu for troubleshooting.

Second, the number of submodels available to the user could be expanded, particularly for the finishing operation. At present, only single machines are available for machining, cutting, and assembly. If the manufacturing option has a number of machining operations in series, for example, the user would have to gather the data so that it would fit in the single machine model. Also, in its present state each submodel can only be used once. A manufacturing process with two assembly operations which are not in ordered sequence could not be modeled effectively. However, adding submodels and more possible combinations of those submodels to the finishing step adds complexity very rapidly because, unlike quality inspection, all the finishing operations change the nature of the part (i.e. cut, add material). This makes the order of processing much more relevant from a design standpoint.

Third, other peripheral process steps can be added to the model. For example, in composite manufacturing raw materials often expire before use. Raw material containers are also considered a reasonably important waste stream. The filament winding application did not address any raw material issues except the percentage of raw material which is discarded. This may be all the design engineer can estimate; however, in certain circumstances a system which orders and processes raw materials may be of great benefit. Other peripheral systems which could be included are shipping, more complex quality systems and labor shift patterns, and multi-product manufacturing options.

Fourth, the reporting of environmental data could be expanded by developing or using current intelligent systems which utilize the environmental laws and regulations to categorize waste streams. The complexity of the regulations did not allow this type of reporting to be included in this research due to time constraints. After talking to many experts in the field it became obvious that this type of categorization was, in itself, a research project.

Fifth, more advanced output analysis techniques could be included. Further work on the simulation should include adding minimum and maximum values, line graphs and histograms to help the user better analyze the simulation output. Currently, only average values are used in the output reports. Other output techniques which could be included are sensitivity analysis, design of experiments, and some form of multi-variate decision analysis techniques such as the analytical hierarchy process. Genetic algorithm techniques are also currently being investigated as a possible addition to this type of simulation. These techniques optimize a certain output index, made up of dependent variables, by running a large number of simulations that make "intelligent" changes to the independent variables.

Other research possibilities include designing and developing these type of modular simulations for other manufacturing technologies. Filament winding is only one of the many manufacturing options for composite materials. Work on modular simulations for hand lay-up, pultrusion, and other composite manufacturing options are being planned at The University of Alabama in Huntsville. Other technologies which could also be studied include the electronic, steel, and automotive industry. More advanced work on chemical and other continuous processing methods could also be very beneficial since continuous processing methods oftentimes have a more detrimental effect on the environment.

7.2 Genetic Algorithms and optimization

A genetic algorithm approach was developed to optimize parameters associated with a manufacturing process. A small problem derived first in order to test the communication between the Witness simulation language and the genetic algorithm code. After this was completed, a larger, more realistic version of a manufacturing system was coded and linked to the genetic

algorithm code. From this initial work it is clear the GA is potentially an effective search method for optimizing the parameters associated with a manufacturing line. In both lines studied, the GA outperformed both an intuitive approach and a random search routine. There are still a number of questions to be answered. These questions include:

Is there another search method (such as a derivative search) that is more effective than the GA?

If the GA is run for more generations, is a better solution obtained?

How well will the GA optimization approach work when the size and complexity of the lines are increased?

Will the GA optimization approach be able to effectively handle multiple optimization objectives?

Future research includes the incorporation of the filament winding model developed by UAH. This model incorporates environmental and energy information which was lacking in the other two models developed. Other plans include development of metrics to ascertain the effectiveness of the GA and comparison to other methods. Finally, a methodology to evaluate the appropriateness of the fitness function under various scenarios will be undertaken.

7.3 CAV and other applications

Future plans, as related to the CAV/ATD simulation, are to develop similar simulations for parts of this type produced by the Automated Fiber Placement (AFP) process (proposed by Alliant for use in Crusader). In the future the VARTM and AFP capabilities derived from CAV will be generalized and integrated into the DTAME simulation system.

7.4 Communications and security

Currently, authentication is performed with "basic" authentication, which is about as secure as telnet (passwords are set plain text). This is fine for preventing casual surfer from entering your site. What we would like to add is support for "Secure Socket Layer Protocol". SSL would make your transactions with the project weakly secure with a "export" browser *, or very secure with a browser that supports longer keys. Apache keeps very detailed logs of all transactions, and these logs could be used to tell not only when updates were made (not a problem... the database has

that capability), but the last versions of each section the user viewed. This would allow generation of a "What's New" section for each user as they log in or reload the main page. It would be nice to be able to generate a hard copy (or soft copy) of the entire project in a portable format. This may not be easy, as some formats can be easily made device independent and hard copied (postscript, html, info, pdf, dvi, and other) and some cannot (vrml, quicktime, mpeg, etc.).

7.5 Integrations

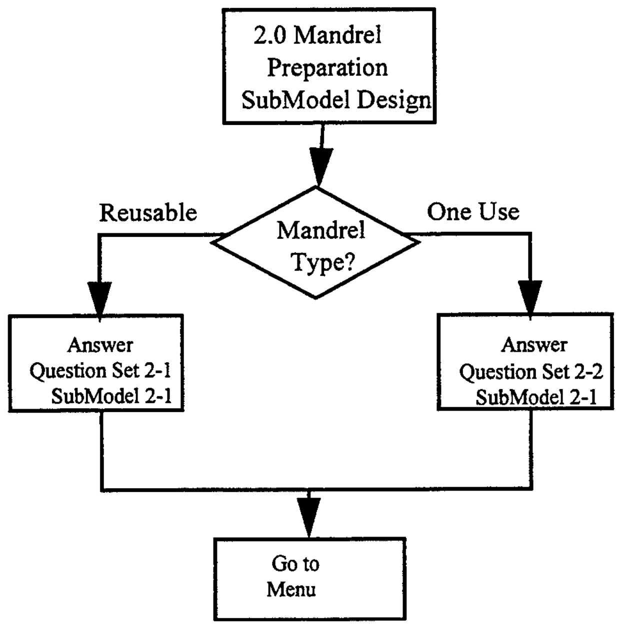
A tighter integration of the prototype parts is needed. Currently the acquisition and simulation components are integrated on a WinTel platform. The communications facility is integrated in the sense that all team members can use it. We hope to expand these efforts. Ideally all of the components will be able to operate on the major platforms and connect to a network database and distribution facility. This will allow for a common exchange of data that is vital in an area where there are many different disciplines and experts who are geographically distributed.

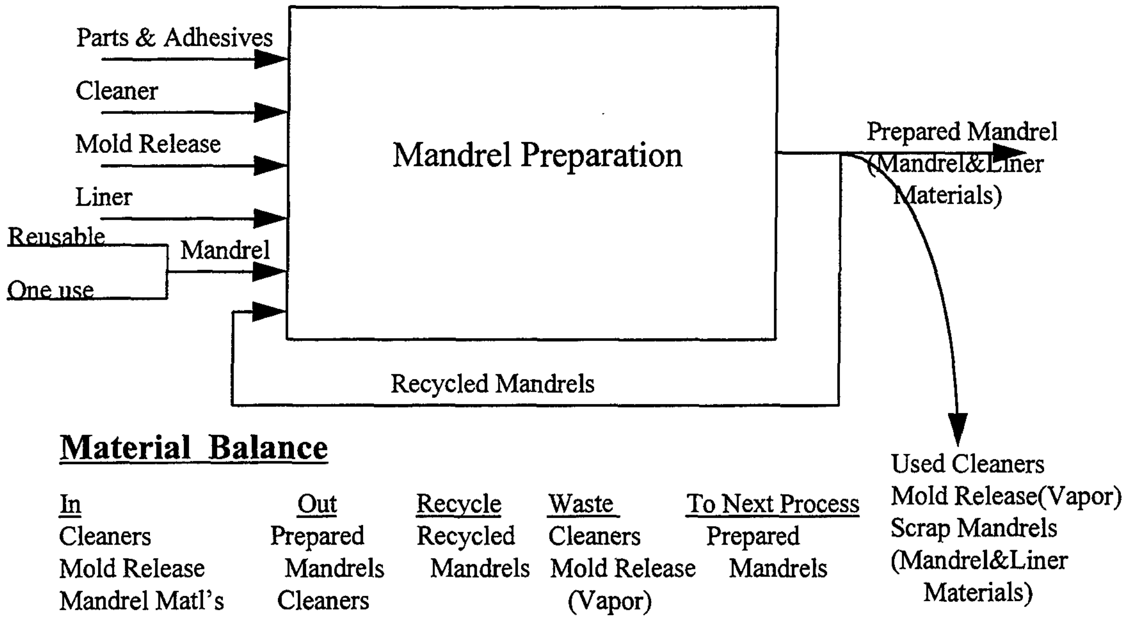
7.6 Concluding comments

This research is focused on improving the performance and production processes of composite materials through the use of advanced design and manufacturing simulation tools. Ultimately, through the use of these tools, a design engineer will be able to produce a high quality design for a composite part that takes full advantage of all of the benefits associated with use of a composite material and avoiding all of the disadvantages. Some steps toward this ideal have been taken; more can be taken.

APPENDIX A

Decision Tree Diagrams Process Flow Diagrams and Material Balances and Question Sets for Filament Winding Individual Processing Steps


2.0 Mandrel Preparation SubModel Design
Mandrel Type?
Reusable
One Use
Answer Question Set 2-1 SubModel 2-1
Answer Question Set 2-2 SubModel 2-1
Go to Menu



Material Balance

In	Out	Recycle	Waste	To Next Process
Cleaners Mold Release Mandrel Matl's Liner Matl's Parts Adhesives	Prepared Mandrels Cleaners Mold Release (Vapor) Scrap Mandrels	Recycled Mandrels	Cleaners Mold Release (Vapor) Scrap Mandrels	Prepared Mandrels

Equations

X designates amount of material coming into submodel
Y designates amount of material leaving submodel

Solvents: $X_{ns} + X_{rs} = Y_{ws} + Y_{sv} + Y_{rs}$

X_{ns} = New Solvent
X_{rs} = Recycled Solvent
Y_{ws} = Waste Solvent
Y_{sv} = Solvent Vapors
Y_{rs} = Recycled Solvent

Mold Release: $X_{mr} = Y_{wmr} + Y_{dmr}$ where:

X_{mr} = Mold Release coming in
Y_{wmr} = Waste Mold Release
Y_{dmr} = Mold Release discarded as raw material

Liner, Parts and Mandrel Materials: $X_m = Y_{pm} + Y_{sm} + Y_{drm}$ where:

X_m = Mat'ls coming in
Y_{pm} = Mat'ls in prepared mandrel
Y_{sm} = Mat'ls in scrap mandrel
Y_{drm} = Mat'ls discarded as raw material

Mandrel Preparation
Question Set 2-1

Materials

Mold Release   Yes___ No (X) If yes: Name list/ insert MSDS info/cost
Amount used per mandrel (0)______
% discarded as unused mold release(0)______

Liner Mat'ls   Yes___ No (X) If yes: How many materials used(0)_______[0,1,2]
Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
% discarded as unused raw material(0)_______

Parts   Yes___No(X)__If yes: How many different parts used(0)______[0,1,2]
Name list/ insert MSDS info/cost
Number used per assembly(0)______
Weight(0)______
% discarded as unused parts(0)______

Adhesives   Yes___ No (X) If yes: How many materials used(0)_______[0,1,2]
Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
% discarded as unused raw material(0)_______

Cleaner(for cleaning mandrels)   Yes___ No (X) If yes: Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
Recycled Yes (X) No____
% Recycled 0-100%
% Released to Air 0-(100-%Recycled)
% Solid/liquid waste (100-[%Recycled + %Vapor])

Mandrels
Number Available(1000)_______
Cost(0)_______
Weight(0)_______
How many uses before discarding?(1000)_________[deterministic or probabilistic]
Do scrap parts during mandrel preparation need to go to mandrel removal station for disassembly? Yes____No(X)

Labor

Is labor required?   Yes (X)No____   If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Set up Procedures

Any set up procedures? Yes___ No (X)

If yes: Frequency of setup? # of cycles between setups

Labor? Type general/(maintenance) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Cycle Time

Cycle time? Type (deterministic)/triangular/probabilistic Parameters ________

Energy Usage

Energy Usage? Yes__ No (X) If yes: Rate? Kw

Configuration

# of Machines? (1)-20

Batch Size?(1)___

Quality

% Scrap? (0)-100%

% Recycle? (0)-[100- % Scrap]%

% Good Parts equals [100-[% Scrap + % Recycle]

Mandrel Preparation
Question Set 2-2

Materials

Mandrels — Yes___ No (X) If yes: Name list/ insert MSDS info/cost
Weight(0)______
% discarded as unused parts(0)______

Mold Release — Yes___ No (X) If yes: Name list/ insert MSDS info/cost
Amount used per mandrel (0)______
% discarded as unused mold release (0)______

Liner Mat'ls — Yes___ No (X) If yes: How many materials used(0)_______ [0,1,2]
Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
% discarded as unused raw material(0)_______

Parts — Yes___ No(X)___ If yes: How many different parts used(0)______ [0,1,2]
Name list/ insert MSDS info/cost
Number used per assembly(0)______
Weight(0)______
% discarded as unused parts(0)______

Adhesives — Yes___ No (X) If yes: How many materials used(0)_______ [0,1,2]
Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
% discarded as unused raw material(0)_______

Cleaner(for cleaning mandrels) — Yes___ No (X) If yes: Name list/ insert MSDS info/cost
Amount used per mandrel(0)_______
Recycled Yes (X) No____
% Recycled 0-100%
% Released to Air 0-(100-%Recycled)
% Solid/liquid waste (100-[%Recycled + %Vapor])

Mandrel Arbor
Number Available(1000)_______
Cost(0)_______
Weight(0)______
How many uses before discarding?(1000)_________[deterministic or probabilistic]
Do scrap parts during mandrel preparation need to go to mandrel removal station for disassembly? Yes____No(X)

Labor

Is labor required? Yes (X)No____ If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes__No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)

If yes: How many different types? 1-10

For each type: Frequency? time between breakdowns

Labor? (maintenance assumed) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Set up Procedures

Any set up procedures? Yes___ No (X)

If yes: Frequency of setup? # of cycles between setups

Labor? Type general/(maintenance) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Cycle Time

Cycle time? Type (deterministic)/triangular/probabilistic Parameters ________

Energy Usage

Energy Usage? Yes___No (X) If yes: Rate? Kw/hr

Configuration

# of Machines? (1)-20

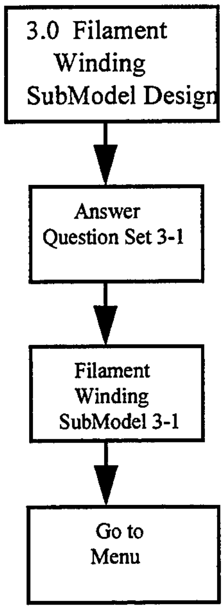
Batch Size?(1)_____

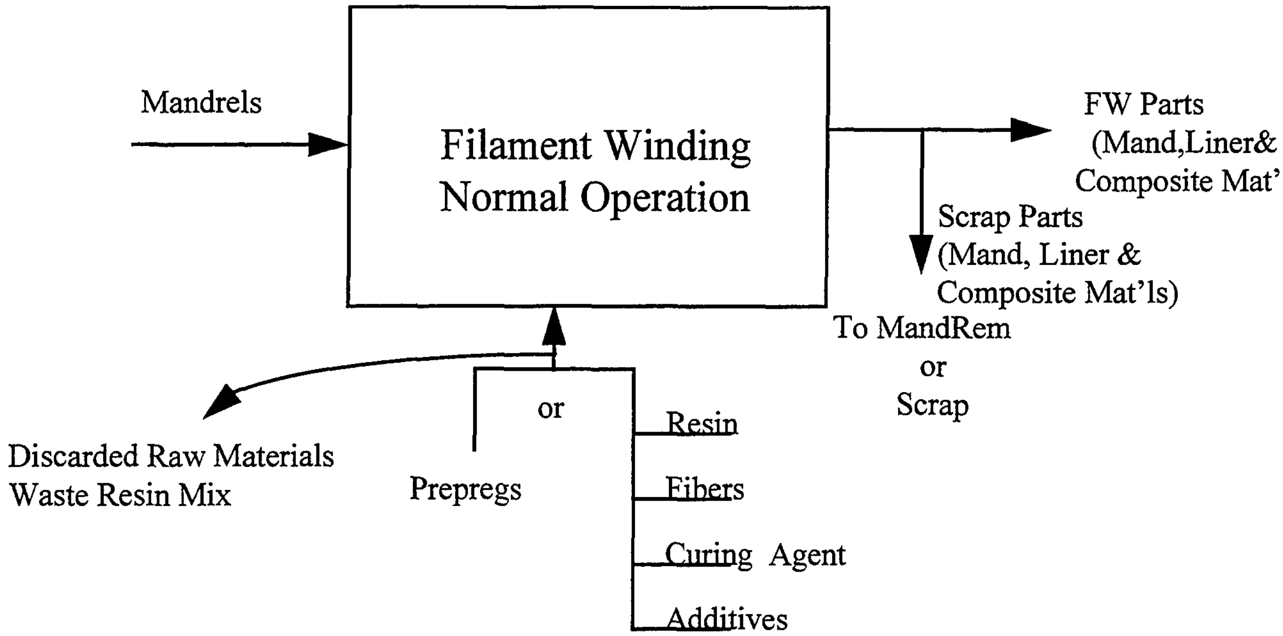
Quality

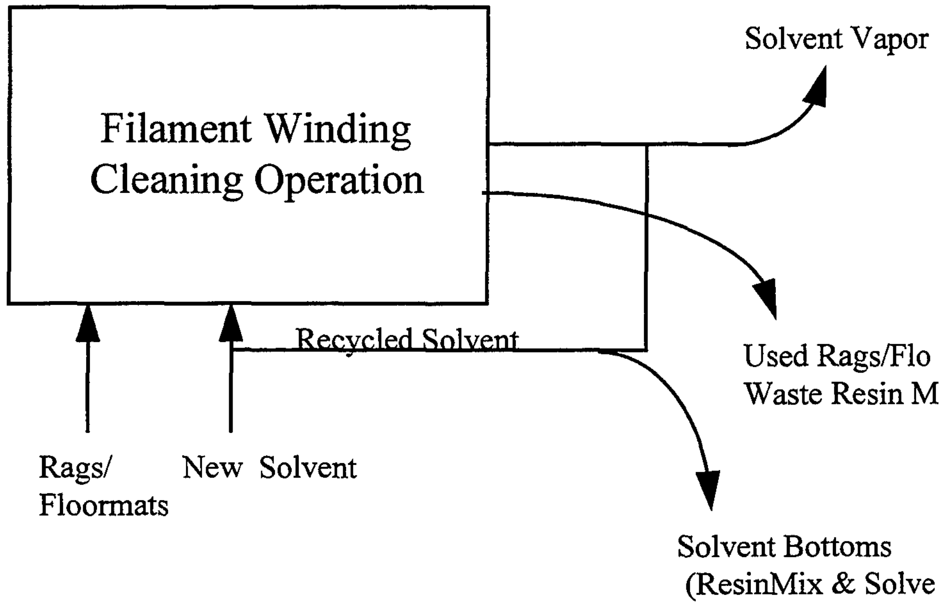
% Scrap? (0)-100%

% Recycle? (0)-[100- % Scrap]%

% Good Parts equals [100-[% Scrap + % Recycle]


3.0 Filament Winding SubModel Design
Answer Question Set 3-1
Filament Winding SubModel 3-1
Go to Menu


Mandrels
Filament Winding
Normal Operation
FW Parts
(Mand,Liner&
Composite Mat'
Scrap Parts
(Mand, Liner &
Composite Mat'ls)
To MandRem
or
Scrap
or
Resin
Fibers
Curing Agent
Additives
Prepregs
Discarded Raw Materials
Waste Resin Mix


Filament Winding
Cleaning Operation
Solvent Vapor
Used Rags/Flo
Waste Resin M
Recycled Solvent
Rags/
Floormats
New Solvent
Solvent Bottoms
(ResinMix & Solve

Material Balance

Normal Operation

In	Out	Waste	Recycle	To Next Process
Prep Mandrel	FW Part	Scrap Parts	None	FW Part
Composite Mat'ls	Scrap Parts	Discarded RM's		
- Resin	Discarded RM's	Resin Mix		
- Fiber	Resin Mix			
- Curing Agent				
- Additives				
- Prepreg				

Cleaning Operation

In	Out	Waste	Recycle	To Next Process
Solvent	Solvent	Solvent	Solvent	None
Rags/Floormats	-Vapor	-Vapor		
Resin Mix	-Liquid	-Liquid		
	Rags/Floormats	Rags/Floormats		
	Resin Mix	Resin Mix&Cuttings		

Equations

X designates amount of material coming into submodel

Y designates amount of material leaving submodel

Composite Mat'ls: $X_{cm} = Y_{cm/fw} + Y_{cm/sp} + Y_{cm/rm} + Y_{cm/s} + Y_{cm/wr}$

X_{cm} = Resin, Fibers, Curing Agent, Additives

$Y_{cm/fw}$ = Comp Mat'ls in FW Part

$Y_{cm/sp}$ = Comp Mat'ls in Scrap Part

$Y_{cm/rm}$ = Disarded Comp Raw Mat'ls

$Y_{cm/s}$ = Comp Mat'ls in Solvent

$Y_{cm/wr}$ = Comp Mat'ls in Waste Resin

Mandrel Mat'ls: $X_{mm/pm} = Y_{mm/sp} + Y_{mm/fw}$

$X_{mm/pm}$ = Mandrel Mat'ls in Prep Mandrel

$Y_{mm/sp}$ = Mandrel Mat'ls in Scrap Part

$Y_{mm/fw}$ = Mandrel Mat'ls in FW Part

Solvents: $X_{ns} + X_{rs} = Y_{ws} + Y_{sv} + Y_{rs}$

X_{ns} = New Solvent

X_{rs} = Recycled Solvent

Y_{ws} = Waste Solvent

Y_{sv} = Solvent Vapors

Y_{rs} = Recycled Solvent

Filament Winding
Question Set 3-1

Materials

Resin Yes___ No (X) If yes: Name list/ insert MSDS info/Cost
Amount in Fil Wound Part (0) ________
% discarded as uncured resin (0)_______
% discarded as cured resin waste(0)_____
% discarded in solvent waste (0)______

Fiber-1 Yes___No (X) If yes: Name list/ insert MSDS info/Cost
Amount in Fil Wound Part (0)________
% discarded as unused fiber (0)_______

Fiber-2 Yes___No (X) If yes: Name list/ insert MSDS info/Cost
Amount in Fil Wound Part (0)________
% discarded as unused fiber (0)_______

Additive-1 Yes___No (X) If yes: Name list/ insert MSDS info/Cost
Amount in Fil Wound Part (0)________
% discarded as unused additive (0)_____

Additive-2 Yes___No (X) If yes: Name list/ insert MSDS info/Cost
Amount in Fil Wound Part (0)________
% discarded as unused additive (0)_____

Curing Agent Yes___No (X) If yes: Name list/ insert MSDS info/Cost
Amount in Fil Wound Part (0)________
% discarded as unused curing agent (0)___

or

Prepreg Yes___No (X) If yes: Name list/ insert MSDS info/Cost
Amount in Fil Wound Part (0)________
% discarded as unused prepreg (0)______

Labor

Is labor required? Yes (X)No____ If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Scheduled Maintenance (other than cleaning)

Any scheduled maintenance? Yes (X) No___
If yes: How many different types? (1)-10
For each type: Frequency? time between breakdowns(39)
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters (1)

Default - Carriage system cleaning

Cleaning (Default Values for wet winding only. Default to no cleaning for prepreg.)

Any normal(Resin not set up)? Yes (X) No___
Type of solvent used: (Acetone)/list/insert MSDS info/cost
Amount of solvent used? (0)
Recycle Yes (X) No___
% Recycled 0 - 100% (70%)
% Vapor 0-(100-%Recycled)% (20%)

% Solid/liquid Waste (100-[% Recycled + % Vapor])(10%)
Frequency of cleaning? time between cleanings (7.5 hrs)
Time required for cleaning? Type (deterministic)/triangular/probabilistic Parameters .5 hrs.
Labor? Type (general assumed) How many? (1)

Any non-normal(Resin set up)? Yes___ No (X)

Type of solvent used: (Acetone)/list/insert MSDS info/cost
Amount of solvent used? (0)
Recycle Yes (X) No___
% Recycled 0 - 100% (70%)
% Vapor 0-(100-%Recycled)% (20%)
% Solid/liquid Waste (100-[% Recycled + % Vapor])(10%)
Frequency of cleaning? time between cleanings (7.5 hrs)

Time required for cleaning? Type (deterministic)/triangular/probabilistic Parameters .5 hrs.
Labor? Type (general assumed) How many? (1)

Set up Procedures

Any set up procedures? Yes (X) No___
If yes: Frequency of setup? # of cycles between setups(1)
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic
Parameters .083-1hr /spindle (depending on size of mandrel)

Cycle Time (get from manufacturer of machine)

Cycle time? Type (deterministic)/triangular/probabilistic Parameters _________

Energy Usage

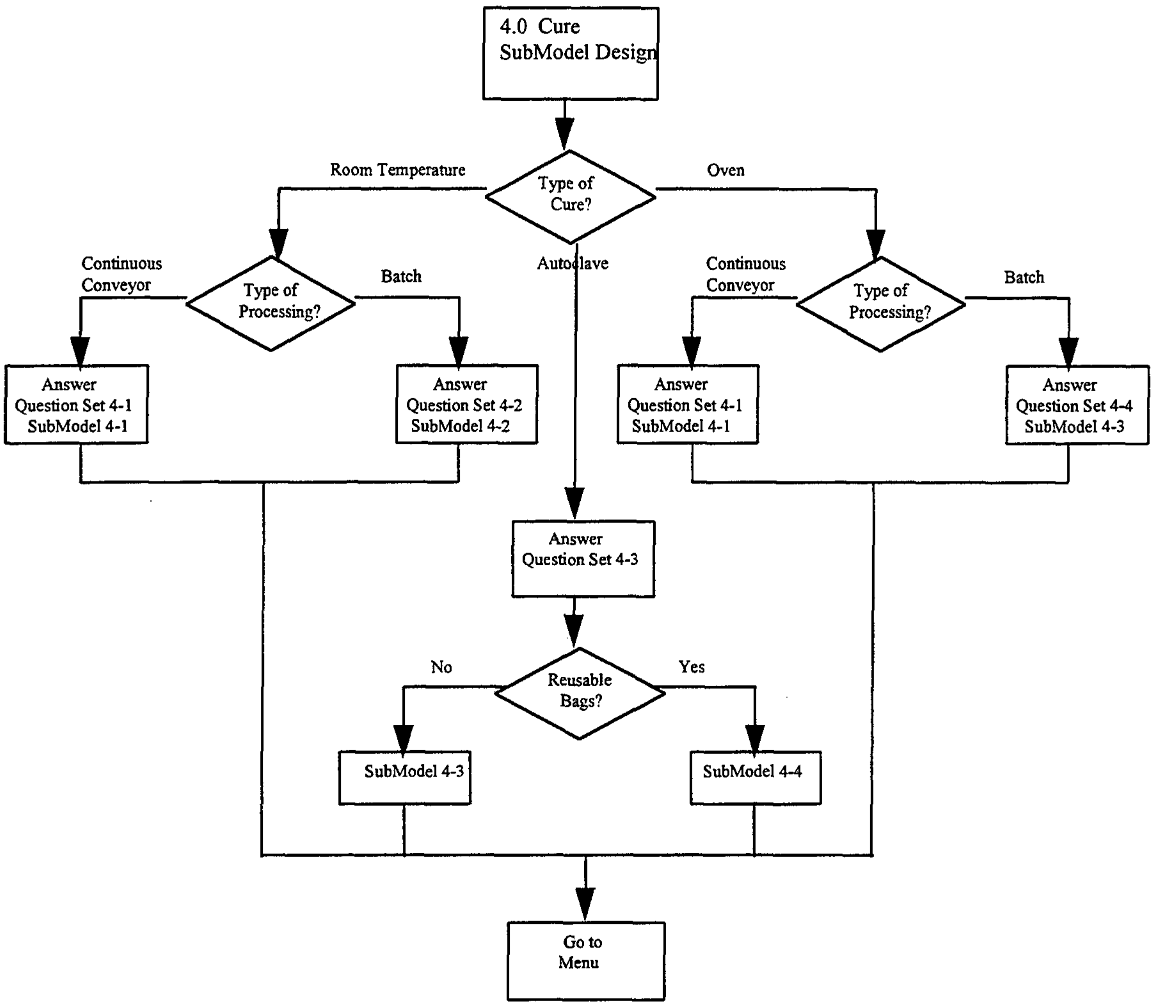
Energy Usage? Yes___ No (X) If yes: Rate? Kw

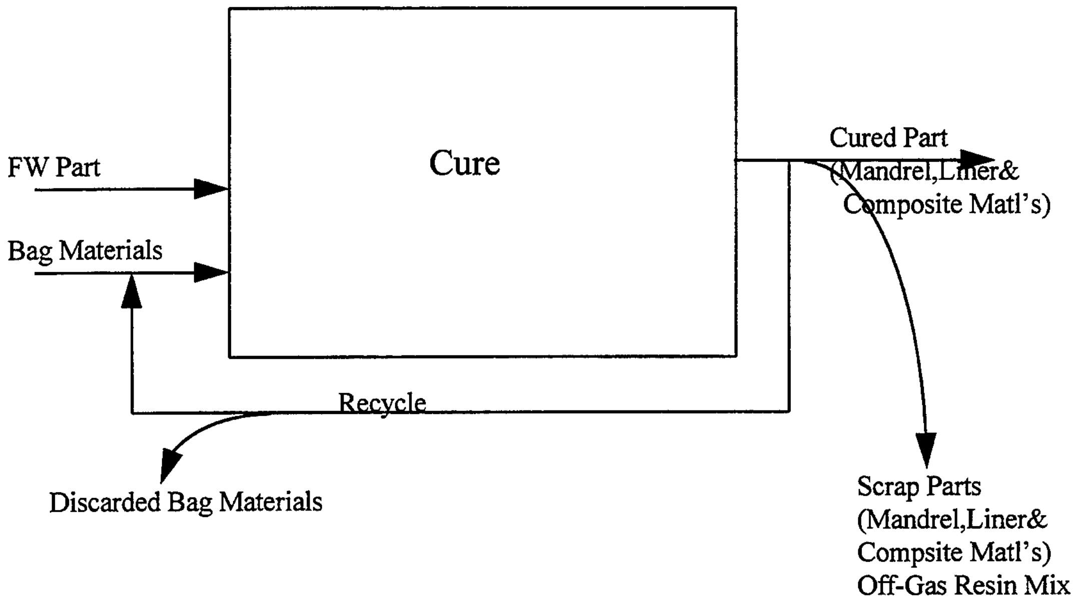
Configuration

# of Machines? (1)-20
# of Spindles/machine (1)-N
Buffer Capacity min of N

Quality

% Scrap? (0)-100%
% Good Parts equals [100-% Scrap]


4.0 Cure
SubModel Design
Type of
Cure?
Room Temperature
Oven
Autoclave
Continuous
Conveyor
Type of
Processing?
Batch
Continuous
Conveyor
Type of
Processing?
Batch
Answer
Question Set 4-1
SubModel 4-1
Answer
Question Set 4-2
SubModel 4-2
Answer
Question Set 4-1
SubModel 4-1
Answer
Question Set 4-4
SubModel 4-3
Answer
Question Set 4-3
Reusable
Bags?
No
Yes
SubModel 4-3
SubModel 4-4
Go to
Menu



Material Balance

In	Out	Recycle	Waste	To Next Process
FW Part	Cured Parts	Bag Mat'ls	Scrap Parts	Cured Parts
Bag Mat'ls	Scrap Parts		Bag Mat'ls	
	Bag Mat'ls			

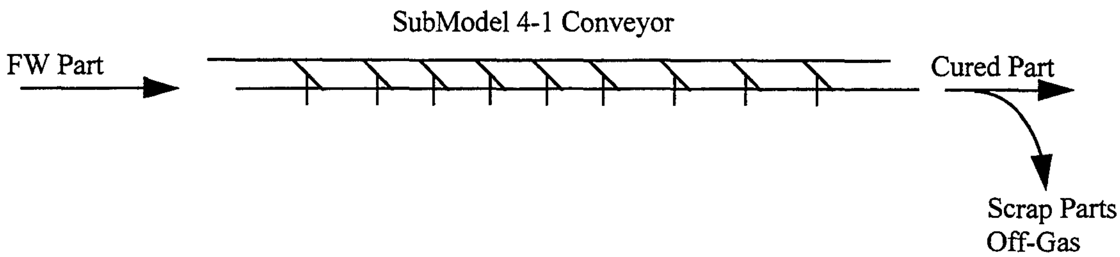
Equations

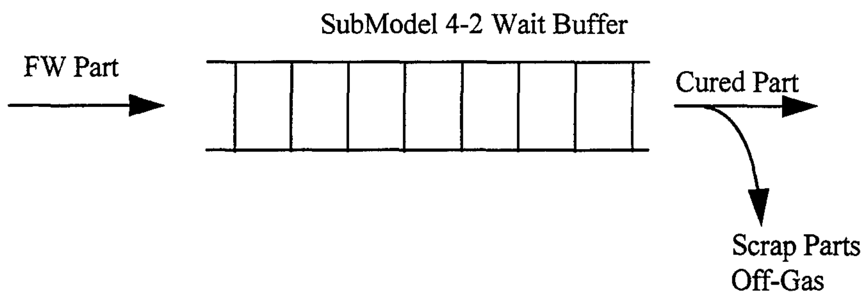
Bag Materials: $X_{nb} + X_{rb} = Y_{db} + Y_{rb}$

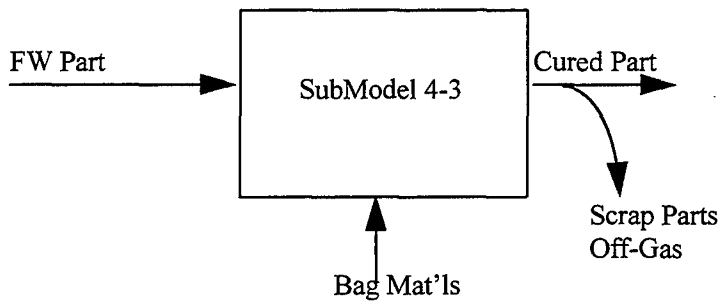
X_{nb} = New Bags used in process
X_{rb} = Recycled Bags
Y_{db} = Discarded Bags
Y_{rb} = Recycled Bags

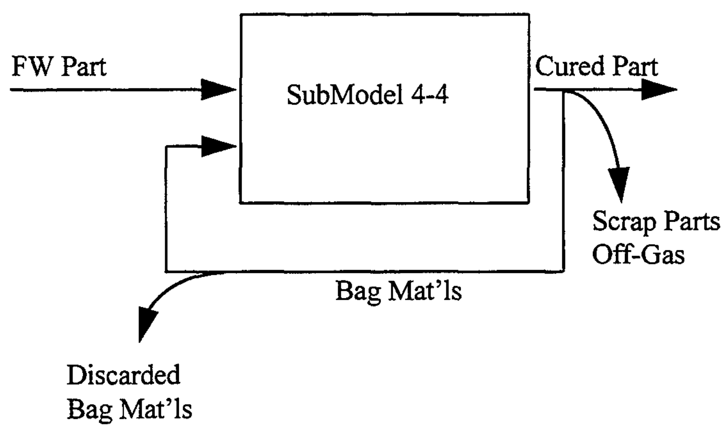
Liner , Mandrel& Composite Mat'ls: $X_{lmc} = Y_{lmc/pm} + Y_{lmc/sm} + Y_{lmc/v}$

X_{lmc} = Liner, Mandrel & Composite Mat'ls coming in
$Y_{lmc/pm}$ = Mat'l in prepared mandrel
$Y_{lmc/sm}$ = Mat'l in scrap mandrel
$Y_{lmc/v}$ = Mat'ls in vapor


SubModel 4-1 Conveyor
FW Part
Cured Part
Scrap Parts
Off-Gas


SubModel 4-2 Wait Buffer
FW Part
Cured Part
Scrap Parts
Off-Gas


FW Part
SubModel 4-3
Cured Part
Scrap Parts
Off-Gas
Bag Mat'ls


FW Part
SubModel 4-4
Cured Part
Scrap Parts
Off-Gas
Bag Mat'ls
Discarded
Bag Mat'ls

Cure
Question Set 4-1

Breakdowns

Any breakdowns or work stoppages? Yes____No(X)

If Yes: Frequency? time between breakdowns

Labor? Type general/(maintenance) Amount (1)

Length of time? Type(deterministic)/triangular/probabilistic Parameters______

Configuration

# of Conveyors ______

# of Parts/Conveyor_____

Cycle Time

Cure Time______

Energy Usage

Energy Usage? Yes__No (X) Rate? KW

Quality

% Scrap (0)-100%

% Good parts equals 100-%Scrap

Cure
Question Set 4-2

Cycle Time
Minimum Cure Time?_______
Configuration
Capacity______
Quality
% Scrap (0)-100%
% Good parts equals 100-%Scrap

Cure
Question Set 4-3
(Modules 4-3 & 4-4)

Materials

Bag Materials Yes___No(X) If Yes: Type of Waste Hazardous/(Nonhazardous)
Cost per bag______
Weight______
Reusable: Yes___[use 4-4]No(X)[use4-3]
If Yes:
available______
of uses before being discarded deterministic or probabilistic

Labor

Is labor required? Yes(X) No____ If yes: How many workers needed?(1)

Breakdowns

Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Set up Procedures

Any set up procedures? Yes___ No (X)
If yes: Frequency of setup? # of cycles between setups
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Cycle Time

Cure time? Type (deterministic)/triangular/probabilistic Parameters ________

Energy Usage

Energy Usage? Yes___No (X) If yes: Rate? Kw

Configuration

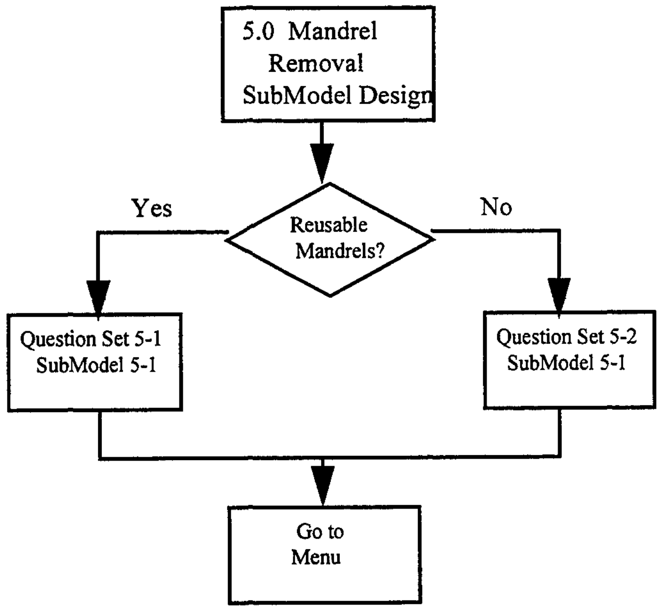
# of autoclaves? (1)-20
Capacity of each autoclave?(1)____
Buffer Capacity ?(min of capacity of autoclave)

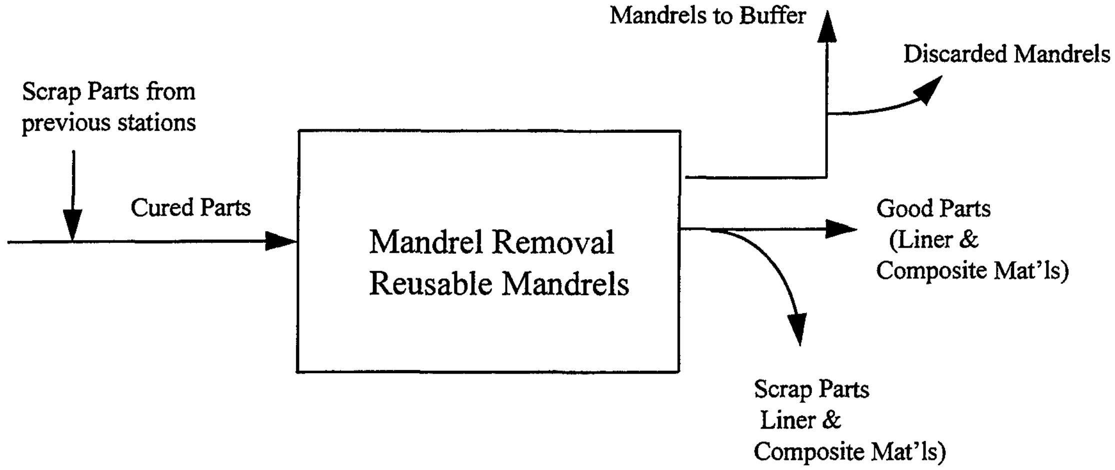
Quality

% Scrap? (0)-100%
% Good Parts equals [100-[% Scrap]

Cure
Question Set 4-4
(Module 4-3)

Labor
Is labor required? Yes___No(X) If yes: How many workers needed?(1)
Breakdowns
Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________
Scheduled Maintenance
Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________
Set up Procedures
Any set up procedures? Yes___ No (X)
If yes: Frequency of setup? # of cycles between setups
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________
Cycle Time
Cure time? Type (deterministic)/triangular/probabilistic Parameters ________
Energy Usage
Energy Usage? Yes___No (X) If yes: Rate? Kw
Configuration
# of Ovens? (1)-20
Capacity of each oven?(1)____
Buffer Capacity ?(min of capacity of oven)
Quality
% Scrap? (0)-100%
% Good Parts equals [100-[% Scrap]


5.0 Mandrel Removal SubModel Design
Reusable Mandrels?
Yes
No
Question Set 5-1 SubModel 5-1
Question Set 5-2 SubModel 5-1
Go to Menu



Material Balance

In	Out	Waste	Recycle	To Next Process
Cured Parts	Mandrels	Mandrels	Mandrels	Good Parts
Scrap Parts	Scrap Parts	Scrap Parts		
	Good Parts			

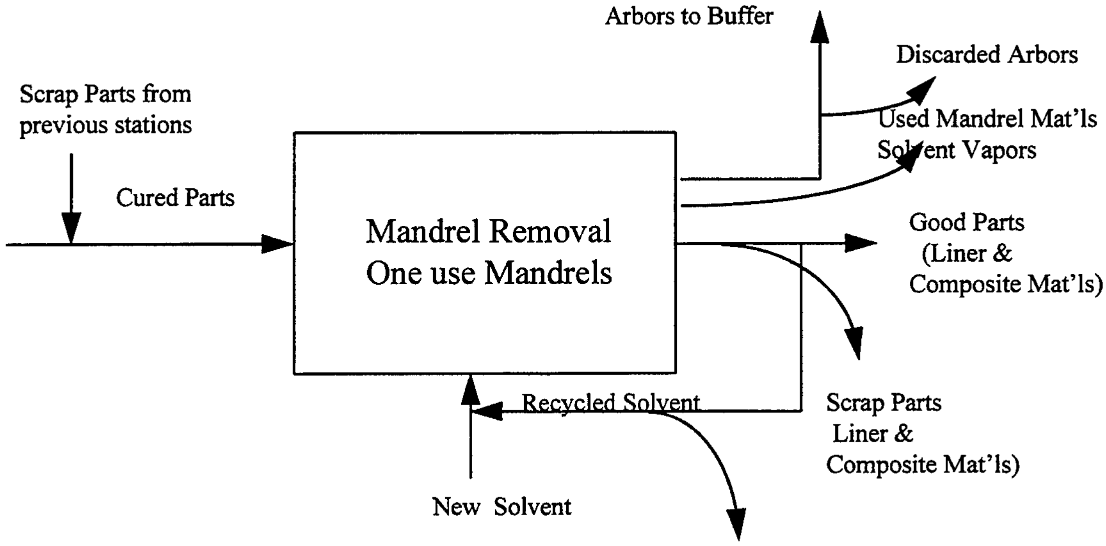
Equations

Mandrels: $X_{m/cp} + X_{m/sp} = Y_{m/b} + Y_{m/d}$

$X_{m/cp}$ = Mandrelsin Cured Parts coming in
$X_{m/sp}$ = Mandrels in Scrap Partsfrom previous stations
$Y_{m/b}$ = Mandrels to buffer
$Y_{m/d}$ = Discarded Mandrels

Liner & Composite Mat'ls: Xlc/cp +Xlc/sp = Ylc/sp + Ylc/gp

$X_{lc/cp}$ = Materials in Cured Parts coming in
$X_{lc/sp}$ = Materials in Scrap Partsfrom previous stations
$Y_{lc/sp}$ = Materials in Scrap Parts
$Y_{lc/gp}$ = Materials in Good Parts



Material Balance

In	Out	Waste	Recycle	To Next Process
Solvent	Solvents	Solvent	Solvent	Good Parts
Cured Parts	-liquid	- liquid	Arbors	
	-vapor	- vapor		
	Mandrel Mat'ls	Mandrel Mat'ls		
	Scrap Parts	Scrap Parts		
	Good Parts	Arbors		
	Arbors			

Equations

X designates amount of material coming into submodel
Y designates amount of material leaving submodel

Mandrel Materials: $X_{mm/cp} = Y_{mm/w}$

$X_{mm/cp}$ = Mandrel Materials in Cured Parts
$Y_{mm/w}$ = Waste Mandrel Material

Solvents: $X_{ns} + X_{rs} = Y_{ws} + Y_{sv} + Y_{rs}$

X_{ns} = New Solvent
X_{rs} = Recycled Solvent
Y_{ws} = Waste Solvent
Y_{sv} = Solvent Vapors
Y_{rs} = Recycled Solvents

Liner & Composite Mat'ls: $X_{lc/cp} = Y_{lc/sp} + Y_{lc/gp}$

X_{lc} = Materials in Cured Parts
$Y_{lc/sp}$ = Materials in Scrap Parts
$Y_{lc/gp}$ = Materials in Good Parts

Arbors: $X_{a/cp} + X_{a/sp} = Y_{a/b} + Y_{a/d}$

$X_{a/cp}$ = Arbors in Cured Parts
$X_{a/sp}$ = Arbors in Scrap Partsfrom previous stations
$Y_{a/b}$ = Arbors to buffer
$Y_{a/d}$ = Discarded Arbors

Mandrel Removal
Question Set 5-1

Labor
Is labor required? Yes (X) No____ If yes: How many workers needed? (1)
Breakdowns
Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________
Scheduled Maintenance
Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________
Set up Procedures
Any set up procedures? Yes___ No (X)
If yes: Frequency of setup? # of cycles between setups
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________
Cycle Time
Cycle time? Type (deterministic)/triangular/probabilistic Parameters _________
Energy Usage
Energy Usage? Yes___No (X) If yes: Rate? Kw
Configuration
# of Machines? (1)-20
Buffer Capacity?_____
Quality
% Scrap? (0)-100%
% Good Parts equals [100-% Scrap]

Mandrel Removal
Question Set 5-2

Materials

Solvent Yes___No_(X)_ If yes: Name list/ insert MSDS info/cost
Amount used per part(0)_______
Recycled Yes (X) No____
% Recycled 0-100%
% Released to Air 0-(100-%Recycled)
% Solid/liquid waste (100-[%Recycled + %Vapor])

Labor

Is labor required? Yes_(X)No____ If yes: How many workers needed?_(1)

Breakdowns

Any breakdowns or work stoppages? Yes___No_(X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount_(1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No_(X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount_(1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Set up Procedures

Any set up procedures? Yes___ No_(X)
If yes: Frequency of setup? # of cycles between setups
Labor? Type general/(maintenance) Amount_(1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Cycle Time

Cycle time? Type (deterministic)/triangular/probabilistic Parameters _________

Energy Usage

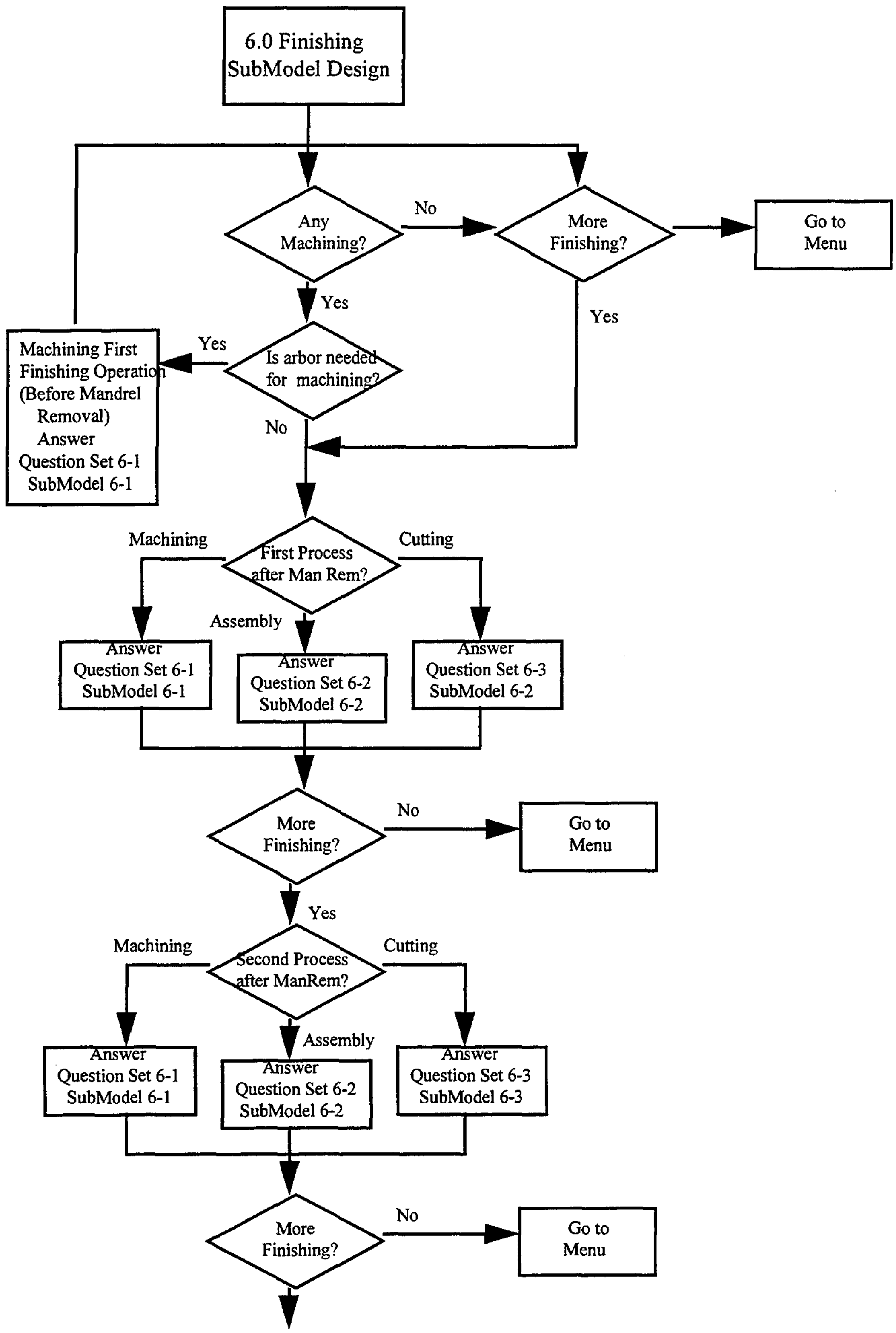
Energy Usage? Yes___No_(X) If yes: Rate? Kw

Configuration

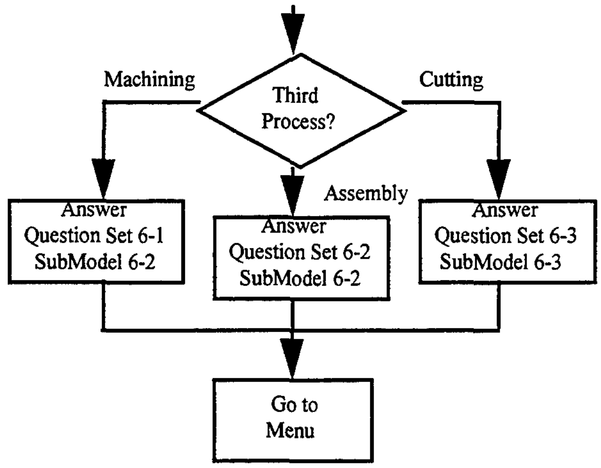
# of Machines?_(1)-20
Buffer Capacity?_____

Quality

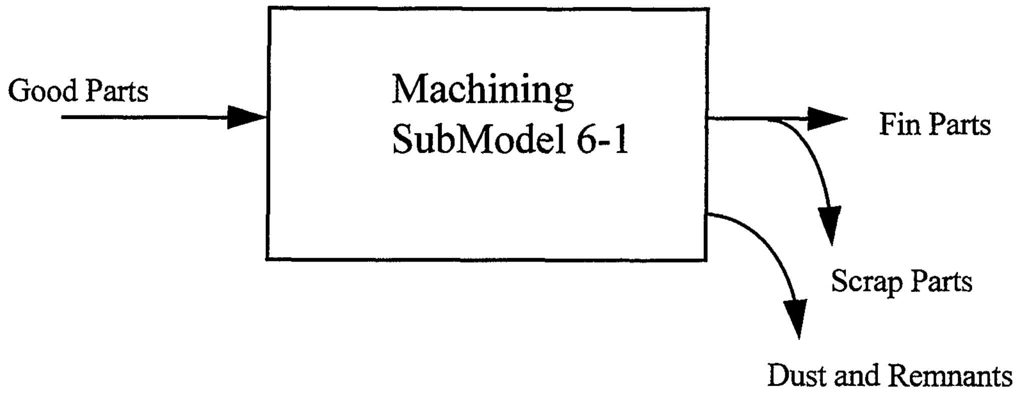
% Scrap?_(0)-100%
% Good Parts equals [100-% Scrap]



Continue on Next Page



Important: Submodels can only be used once in Model (i.e. Machining Submodel is only available if not previously selected.



Materials Balance

In	Out	Waste	Recycle	To Next Process
Good Parts	FinParts	Dust&Remnants		Fin Parts
	Dust	Scrap Parts		
	Scrap Parts			

Equations

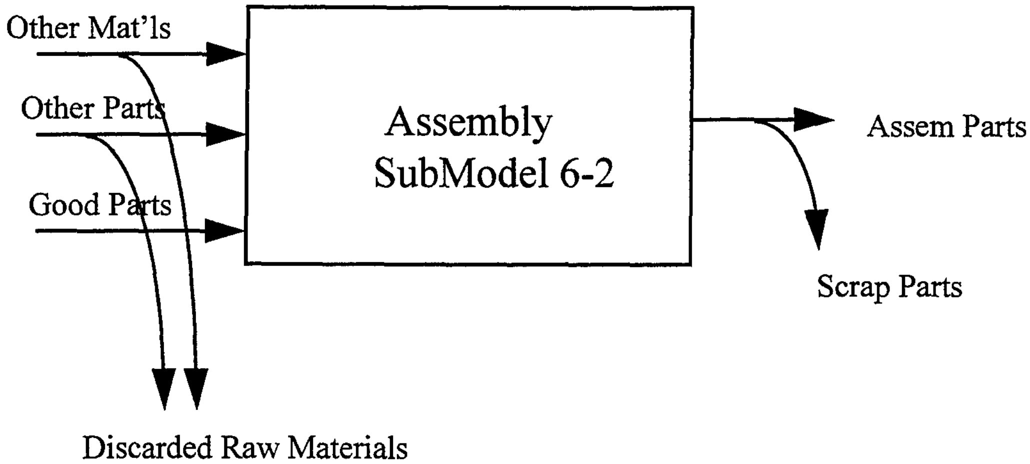
X designates amount of material coming into submodel
Y designates amount of material leaving submodel

Comp & Liner Mat'ls: $X_{clm} = Y_{clm/sp} + Y_{clm/d} + Y_{clm/fp}$

X_{clm} = Mat'ls in parts coming in
$Y_{clm/sp}$ = Mat'ls in scrap parts
$Y_{clm/d}$ = Mat'ls in Dust (assume negligable)
$Y_{clm/fp}$ = Mat'ls in FinParts

Finishing - Machining
Question Set 6-1

Labor
Is labor required? Yes (X) No___ If yes: How many workers needed? (1)
Breakdowns
Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________
Scheduled Maintenance
Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________
Set up Procedures
Any set up procedures? Yes___ No (X)
If yes: Frequency of setup? # of cycles between setups
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________
Cycle Time
Cycle time? Type (deterministic)/triangular/probabilistic Parameters ________
Energy Usage
Energy Usage? Yes___No (X) If yes: Rate? Kw
Configuration
# of Machines? (1)-20
Buffer Capacity?______
Quality
% Scrap? (0)-100%
% Good Parts equals [100-% Scrap]
Waste
% of original material discarded as waste?(0)____



Materials Balance

In	Out	Waste	Recycle	To Next Process
Good Parts	AssemParts	Discarded RM's		AssemParts
Other Parts	Scrap Parts	Scrap Parts		
Other Mat'ls	Discarded RM's			

Equations

X designates amount of material coming into submodel
Y designates amount of material leaving submodel

Comp & Liner Mat'ls: $X_{clm} = Y_{clm/sp} + Y_{clm/am}$

X_{clm} = Mat'ls in parts coming in
$Y_{clm/sp}$ = Mat'ls in scrap parts
$Y_{clm/ap}$ = Mat'ls in assembled parts

Other Parts & Mat'ls: $X_{pm} = Y_{pm/m} + Y_{pm/sp} + Y_{pm/ap}$

X_{pm}= Parts & Mat'ls coming in
$Y_{pm/rm}$ = Discarded RM's
$Y_{pm/sp}$ = Parts & Mat'ls in scrap parts
$Y_{pm/ap}$ = Parts & Mat'ls in assembled parts

Finishing- Assembly
Question Set 6-2

Materials

Other Mat'ls Yes___ No (X) If yes: How many materials used(0)______ [0,1,2]
Name list/ insert MSDS info/cost
Amount used per assembly(0)______
% discarded as unused raw material(0)______

Other Parts Yes___ No (X) If yes: How many different parts used(0)______ [0-4]
Name list/ insert MSDS info/cost
Number used per assembly(0)______
Weight(0)_____
% discarded as unused parts(0)______

Labor

Is labor required? Yes (X) No____ If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes___ No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Set up Procedures

Any set up procedures? Yes___ No (X)
If yes: Frequency of setup? # of cycles between setups
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Cycle Time

Cycle time? Type (deterministic)/triangular/probabilistic Parameters ________

Energy Usage

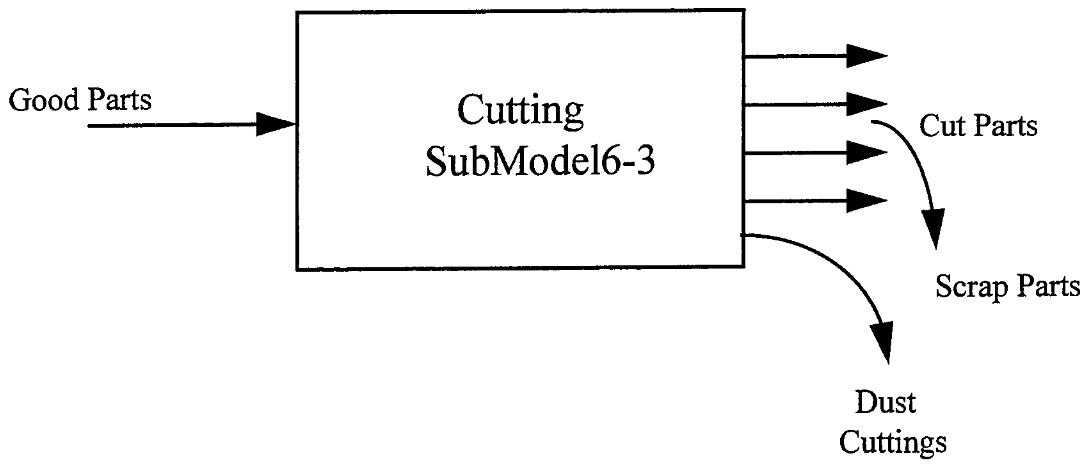
Energy Usage? Yes___ No (X) If yes: Rate? Kw

Configuration

# of Machines? (1)-20
Buffer Capacity?______

Quality

% Scrap? (0)-100%
% Good Parts equals [100-% Scrap]



Materials Balance

In	Out	Waste	Recycle	To Next Process
Good Parts	CutParts	Dust		CutParts
	Dust	Scrap Parts		
	Cuttings	Cuttings		
	Scrap Parts			

Equations

Comp & Liner Mat'ls: $X_{clm} = Y_{clm/sp} + Y_{clm/d} + Y_{clm/cp}$

X_{clm} = Mat'ls in parts coming in

$Y_{clm/sp}$ = Mat'ls in scrap parts

$Y_{clm/d}$ = Mat'ls in Dust (assume negligable)

$Y_{clm/cp}$ = Mat'ls in Cut parts

Finishing- Cutting
Question Set 6-3

Labor

Is labor required? Yes (X) No____ If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes___ No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Set up Procedures

Any set up procedures? Yes___ No (X)
If yes: Frequency of setup? # of cycles between setups
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Cycle Time

Cycle time? Type (deterministic)/triangular/probabilistic Parameters ________

Energy Usage

Energy Usage? Yes___ No (X) If yes: Rate? Kw

Configuration

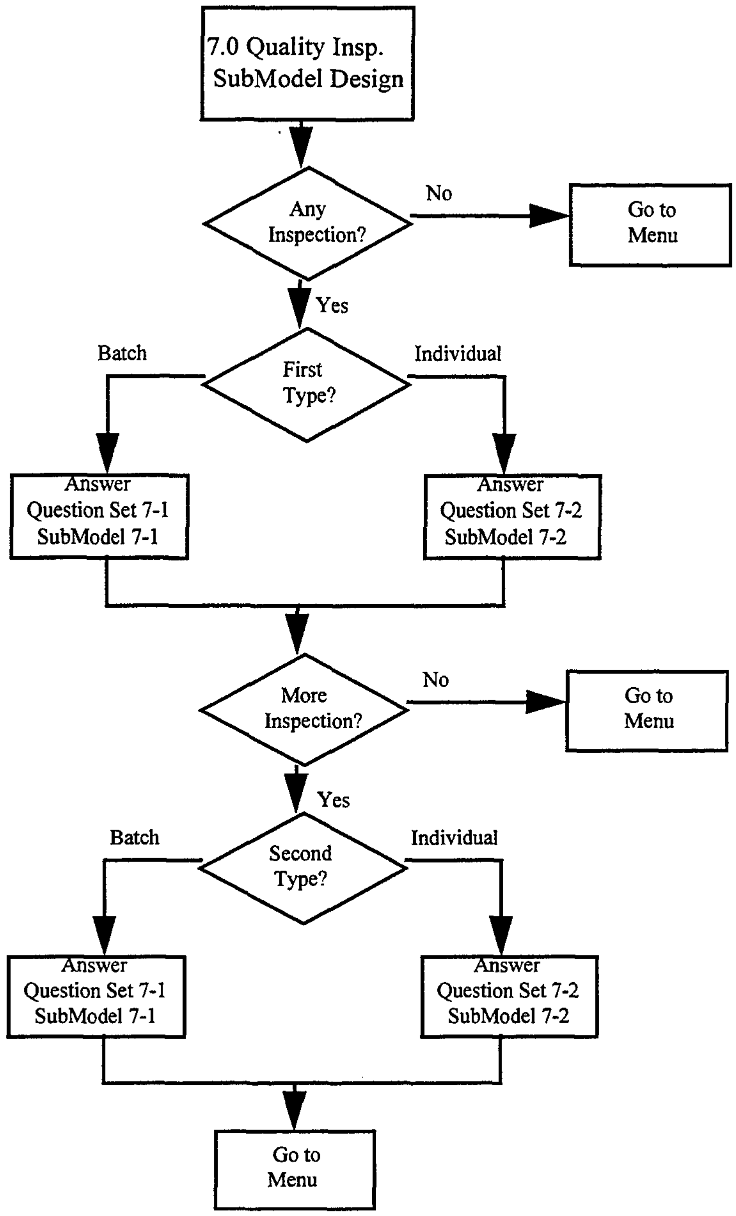
# of Machines? (1)-20
Buffer Capacity?_______
# of parts cut from original part?_____

Quality

% Scrap? (0)-100%
% Good Parts equals [100-% Scrap]

Waste

% of original material discarded as waste?(0)______


7.0 Quality Insp. SubModel Design
Any Inspection?
No
Go to Menu
Yes
Batch
First Type?
Individual
Answer Question Set 7-1 SubModel 7-1
Answer Question Set 7-2 SubModel 7-2
More Inspection?
No
Go to Menu
Yes
Batch
Second Type?
Individual
Answer Question Set 7-1 SubModel 7-1
Answer Question Set 7-2 SubModel 7-2
Go to Menu

Quality Inspection
Question Set 7-1
Labor
Is labor required? Yes (X) No____ If yes: How many workers needed? (1)
Breakdowns
Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________
Scheduled Maintenance (other than cleaning)
Any scheduled maintenance? Yes___No(X)
If yes: How many different types? (1)-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters (1)
Set up Procedures
Any set up procedures? Yes___No (X)
If yes: Frequency of setup? # of cycles between setups(1)
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic
Parameters _______
Cycle Time (get from manufacturer of machine)
Cycle time? Type (deterministic)/triangular/probabilistic Parameters _________
Energy Usage
Energy Usage? Yes___No (X) If yes: Rate? Kw
Configuration
# of Inspection Stations? (1)-20
Buffer Capacity min of N
Quality
Batch Size?____
Sample size?____
% Batches Scrapped? (0)-100%
% Good Batches equals [100-% Scrap]

Quality Inspection
Question Set 7-2
Labor
Is labor required? Yes (X) No____ If yes: How many workers needed? (1)
Breakdowns
Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________
Scheduled Maintenance (other than cleaning)
Any scheduled maintenance? Yes____ No(X)
If yes: How many different types? (1)-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _____
Set up Procedures
Any set up procedures? Yes____No (X)
If yes: Frequency of setup? # of cycles between setups(1)
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic
Parameters _______
Cycle Time (get from manufacturer of machine)
Cycle time? Type (deterministic)/triangular/probabilistic Parameters _________
Energy Usage
Energy Usage? Yes___No (X) If yes: Rate? Kw/hr
Configuration
# of Inspection Stations? (1)-20
Buffer Capacity ?_____
Quality
% Scrapped? (0)-100%
% Good Parts equals [100-% Scrap]

APPENDIX B

Assumptions for Filament Winding Application

Assumptions

1) The product must be made and the choice is between which manufacturing alternative is better. The product is assumed to have similar pre and post fabrication impacts of the environment.

2) All raw materials are available when needed. There are no order problems. Raw material is created as needed by the simulation.

3) All raw materials that do not end up as finished product are discarded as waste. Solvents can be recycled.

4) General labor can be assigned all manufacturing tasks. Maintenance labor can be assigned all maintenance tasks. Set-up and cleaning are optional. Labor must be utilized during the entire cycle time.

5) Parts are independent from a quality perspective. There is no autocorrelation.

6) All machine operations (i.e. cycle time, time between failure, set-up times, etc.) are the same for all machines with a similar function (i.e. mandrel preparation). Any number of parallel machines can be used for the same function.

7) One mandrel is used per wound part.

8) Laboratory waste, raw material containers, rags, and floormats are not kept track of during the simulation.

9) The equipment is dedicated to the production of one product. If this is not true breakdowns or scheduled maintenance can be used to help model the duel use of the equipment.

10) Any recycling within the process step assumes the cycle is the same as the normal cycle time and no additional materials are used.

11) Finished product from one machine will be either pushed to the buffer of the next machine where it will be pulled by that machine or if the buffer capacity is equal to 0 it will be pushed directly to the next machine.

12) There is equal priority for labor among all machine sites.

13) Poor quality material is scrapped as soon as possible.

14) Raw materials can be discarded as waste.

15) Buffers are First in First out (FIFO).

16) All materials used for preparing the mandrel are used during mandrel preparation. If the mandrel preparation is done after the mandrel is placed on the winder a cycle time of .001 should be used for mandrel preparation and all material information should be input as if mandrel preparation is a separate process step. The set up time for filament winding can be used for the mandrel preparation cycle time.

17) Breakdowns, scheduled maintenance, and cleaning is based on time. Set up is based on operating cycles.

18) A twenty four hour working schedule per day is assumed. No allowances are made during the day for breaks, shift changes, etc. If this is substantially different than what can be expected in the real world shift patterns can be set up using WITNESS.

19) Normal cleaning is assumed before all scheduled and unscheduled maintenance activities begin.

20) No submodel can be used more than once in any manufacturing option.

21) No time allotted for transfering between machines.

APPENDIX C

Definitions of Simulation Variables and Attributes for Filament Winding Application

Sub Model Definitions

Scrap Variables are counters if Quality=1 (bad) for given situations

During Finishing:

ScrapF = Counter for all finishing if mandrel removal has already taken place

ScrapF0 = If Assem>0 and Assem<Cut increment by 1
Scrap includes Assembly Materials and Parts. Part was assembled before being cut. Use full amount/# of cut parts.

ScrapF1 = If Assem>0 and Assem>Cut increment by 1
Scrap includes Assembly Materials and Parts. Part was assembled after being cut. Use full amount of assembled parts

ScrapF2 = If Mach>1 and Cut=0 increment by 1
Part has been machined but not cut. Amount of composite and liner materials equals (original-%machined).

ScrapF3 = If Mach=0 and Cut>1 increment by 1
Part has been cut but not machined. Amount of composite and liner materials equals (origina/-%cuttings)/# of cut parts.

ScrapF4 = If Mach>1 and Cut>1 increment by 1
Part has been machined and cut. Amount of composite and liner materials equals (original -(% cuttings+ %machined)/# of cut parts

ScrapF5 = If Mach=0 and Cut=0 increment by 1
Part has not been machined nor cut. Amount of composite and liner materials equals original amount.

ScrapMa= Number of scrap parts from machining operation.

ScrapA = Number of scrap parts from assembly operation.

ScrapCut = Number of scrap parts from cutting operation.

During Cure:

ScrapC = If mandrel removal has not occured increment by 1
Scrap will include mandrel materials.

Scrap (C1-C4) = Counter for various curing submodels.

Variables that count the number of good finished parts:

Ship___ = Number of good finished parts from "___" process step
Example ShipC is the number of good finished parts from the cure process.

Variables which track solvent usage during Filament Winding cleaning operation:

Solv1add = Amount of solvent to add to variable Solv1use during normal cleaning operation of Filament Winding.

Solv1use = Total amount of solvent 1 used during simulation during normal cleaning of Filament Winding.

Solv2add = Amount of solvent to add to variable Solv2use during heavy duty cleaning operation of Filament Winding.

Solv2use = Total amount of solvent 2 used during simulation during heavy duty cleaning of Filament Winding.

Variables which track the number of new reusable parts:

NewMand = Counter for new mandrels coming into the process. If attribute "uses" > "manduses" increment by 1.

NewBags = Counter for new bags coming into the process. If attribute "usesb" > "baguses" increment by1.

Variables which replace attributes to parts after a "production" machine operation:

MRUses = Replaces attribute "Uses" to mandrel after mandrel removal step.

MRManUse = Replaces attribute "ManUses" to mandrel after mandrel removal step.

Cut___ = Replaces attribute "___" to new cut parts after cutting step.

Distribution for process steps:

Qual___ = Quality distribution for processing steps. (% Good)

Group 1 Attributes

Assem = (0,1,2,3) 0 indicates no assembly has taken place.
1,2, or 3 is the order in which it has taken place within the three finishing operations.

Cure = (0,1,2) Indicates the number of curing operations that have taken place on part.

Cut = (0,1,2,3) 0 indicates no cutting has taken place.
1,2, or 3 is the order in which it has taken place within the three finishing operations.

FW = (0,1) Indicates the number of filament winding operations that have taken place on part.

Machine = (0,1,2,3) 0 indicates no machining has taken place.
1,2, or 3 is the order in which it has taken place within the three finishing operations.

ManUses = The number of times the mandrel will be allowed to be used. Can have a distribution.

MandRem = (0,1) Indicates the number of mandrel removal operations that have taken place on part.

MandPrep = (0,1) Indicates the number of mandrel preparation operations that have taken place on part.

QIB = (0,1) Indicates the number of batch quality inspections that have taken place on part.

QII = (0,1) Indicates the number of individual quality inspections that have taken place on part.

Quality = (0,1,2) Indicates the quality coming out of a particular processing element. 0 is good, 1 is scrap, 2 is recycle.

Uses = Indicates the number of times the mandrel has been used.

Group 2

BagUses = The number of times the mandrel will be allowed to be used. Can have a distribution.

UsesB = Indicates the number of times the mandrel has been used.

APPENDIX D

Material and Miscellaneous Databases and Report Equations for Filament Winding Application

Material Database	Mold Release	MP Part1	MP Part2	MPAdhesive1	MP Adhesive 2	Liner Mat'l1	Liner Mat'l2	Mandrel	Mand Mat'l1	Mand Mat'l2	Resin
Information											
Trade Name											
Generic Name											
Category											
MSDS Category											
Ext Haz Sub-Rep Quantity											
Ext Haz Sub-TPQ											
Toxic Chemical											
TRI Chemical											
SARA H-1	1.00			1.00							1.00
SARA H-2											
SARA P-3											
SARA P-4											
SARA P-5											
Cost	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Inputed by User											
Amount or # used for original part	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		1.00
Weight/part		3.00						30.00			
% Discarded as RM	0.10	0.10				0.10					0.10
% Recycled											
% in Waste Resin Mix											0.10
% in Solvent Waste											0.10
% in Air											
% machined waste						0.00					
% cuttings						0.00					
# of parts in buffer								30.00			
# of times used								100.00			

Misc. Database	
Cut Parts	1
FW Batch Size	3
Cure 3 Batch Size	3
QIBatch # Insp	2
Weeks	52
NRGCost	0.1
ShipC	0
ShipMach	0
ShipAs	0
ShipCut	0
ShipMR	0
ShipQ	1426
OrderC3	0

Material Report Equations

29	Inputed by Simulation	Mold Release
30	Amount Needed /finished part	=B35/MAX(Ship)
31	Avg. lbs needed/week	=B34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	0
34	Amount In	=B18*MandBuff/(1-B20)
35	Amount Out	=SUM(B36:B38)+SUM(B46:B50)
36	Discarded RM's	=B20*B18*MandBuff/(1-B20)
37	Discarded Mat'ls used for Good Parts or WIP	=IF(Liner=0,B18*(ScrapMP+ManRem)-B38,B18*ManRem-B38)
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(B39:B45)
39	Mandrel Prep	=+B18*ScrapMP
40	Fil Winding	=B18*ScrapFW
41	Cure	=B18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,B18*ScrapMR-B40-B18*ScrapC-B18*(ScrapA+ScrapMA+ScrapCut-ScrapF),B18*ScrapMR-B39-B40-B18*ScrapC-B18*(ScrapA+ScrapMA+ScrapCut-ScrapF))
43	Finishing	=B18*(ScrapF2+ScrapF5)+B18/CutParts*(ScrapF3+ScrapF4)
44	Batch QI	=B18*(ScrapQB+(QIBatch*InspNum))/CutParts
45	Ind QI	=B18/CutParts*ScrapQI
46	Machine Waste	0
47	Cuttings	0
48	Waste Resin	0
49	Solvent Bottoms	0
50	Air	0
51	Good Parts	0
52	Amount in WIP	=IF(Liner=0,B18*(MandBuff-(ScrapMP+ManRem)),B18*(MandBuff-ManRem))
53	Recycle	0
54	% Scrap	=B38/B34
55	% Waste	=(SUM(B36:B38)+ SUM(B46:B50))/B34
56	%WIP	=B52/B34
57	%Good	=B51/B34
58	TOTAL	=SUM(B55:B57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(B7>0,B$36,0)
61	Ext Haz Sub-TPQ	=IF(B8>0,B$36,0)
62	Toxic Chemical	=IF(B9>0,B$36,0)
63	TRI Chemical	=IF(B10>0,B$36,0)
64	SARA H-1	=IF(B11>0,B$36,0)
65	SARA H-2	=IF(B12>0,B$36,0)
66	SARA P-3	=IF(B13>0,B$36,0)
67	SARA P-4	=IF(B14>0,B$36,0)
68	SARA P-5	=IF(B15>0,B$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(B7>0,B$34,0)
71	Ext Haz Sub-TPQ	=IF(B8>0,B$34,0)
72	Toxic Chemical	=IF(B9>0,B$34,0)
73	TRI Chemical	=IF(B10>0,B$34,0)
74	SARA H-1	=IF(B11>0,B$34,0)
75	SARA H-2	=IF(B12>0,B$34,0)
76	SARA P-3	=IF(B13>0,B$34,0)
77	SARA P-4	=IF(B14>0,B$34,0)
78	SARA P-5	=IF(B15>0,B$34,0)

9	Inputted by Simulation	MP Parts
30	Amount Needed /finished part	=C35/MAX(Ship)
31	Avg. lbs needed/week	=C32*C19
32	Avg # needed/week	=C34/Weeks
33	Amount in finished part	=C18/CutParts
34	Amount In	=C18*MandBuff/(1-C20)
35	Amount Out	=SUM(C36:C38)+SUM(C46:C51)
36	Discarded RM's	=C20*C18*MandBuff/(1-C20)
37	Discarded Mat'ls used for Good Parts or WIP	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(C39:C45)
39	Mandrel Prep	=C18*ScrapMP
40	Fil Winding	=C18*ScrapFW
41	Cure	=C18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,IF(ScrapF=ScrapMA+ScrapA+ScrapCut,C18*(ScrapMR- ScrapFW+ScrapC)), C18*(ScrapMR-(ScrapFW+ScrapC+ScrapMA))), IF(ScrapF=ScrapMA+ScrapA+ScrapCut,C18*(ScrapMR -(ScrapMP+ScrapFW+ScrapC)), C18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC+ScrapMA))))
43	Finishing	=C33*(ScrapF3+ScrapF4)+C18*(ScrapF2+ScrapF5)
44	Batch QI	=C33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=C33*ScrapQI
46	Machine Waste	0
47	Cuttings	0
48	Waste Resin	0
49	Solvent Bottoms	0
50	Air	0
51	Good Parts	=C33*MAX(Ship)
52	Amount in WIP	=C34-C35
53	Recycle	0
54	% Scrap	=C38/C34
55	% Waste	=(SUM(C36:C38) + SUM(C46:C50))/C34
56	%WIP	=C52/C34
57	%Good	=C51/C34
58	TOTAL	=SUM(C55:C57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(C7>0,C$36*MPPart1Weight,0)
61	Ext Haz Sub-TPQ	=IF(C8>0,C$36*MPPart1Weight,0)
62	Toxic Chemical	=IF(C9>0,C$36*MPPart1Weight,0)
63	TRI Chemical	=IF(C10>0,C$36*MPPart1Weight,0)
64	SARA H-1	=IF(C11>0,C$36*MPPart1Weight,0)
65	SARA H-2	=IF(C12>0,C$36*MPPart1Weight,0)
66	SARA P-3	=IF(C13>0,C$36*MPPart1Weight,0)
67	SARA P-4	=IF(C14>0,C$36*MPPart1Weight,0)
68	SARA P-5	=IF(C15>0,C$36*MPPart1Weight,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(C7>0,C$34,0)
71	Ext Haz Sub-TPQ	=IF(C8>0,C$34,0)
72	Toxic Chemical	=IF(C9>0,C$34,0)
73	TRI Chemical	=IF(C10>0,C$34,0)
74	SARA H-1	=IF(C11>0,C$34,0)
75	SARA H-2	=IF(C12>0,C$34,0)
76	SARA P-3	=IF(C13>0,C$34,0)
77	SARA P-4	=IF(C14>0,C$34,0)

29	Inputed by Simulation	MP Adhesives
30	Amount Needed /finished part	=E35/MAX(Ship)
31	Avg. lbs needed/week	=E34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	=E18/CutParts
34	Amount In	=E18*MandBuff/(1-E20)
35	Amount Out	=SUM(E36:E38)+SUM(E46:E51)
36	Discarded RM's	=E20*E18*MandBuff/(1-E20)
37	Discarded Mat'ls used for Good Parts or WIP	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(E39:E45)
39	Mandrel Prep	=E18*ScrapMP
40	Fil Winding	=E18*ScrapFW
41	Cure	=E18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,IF(ScrapF=ScrapMA+ScrapA+ScrapCut,E18*(ScrapMR-(ScrapFW+ScrapC)),E18*(ScrapMR-(ScrapFW+ScrapC+ScrapMA))),IF(ScrapF=ScrapMA+ScrapA+ScrapCut,E18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC)),E18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC+ScrapMA))))
43	Finishing	=E33*(ScrapF3+ScrapF4)+E18*(ScrapF2+ScrapF5)
44	Batch QI	=E33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=E33*ScrapQI
46	Machine Waste	0
47	Cuttings	0
48	Waste Resin	0
49	Solvent Bottoms	0
50	Air	0
51	Good Parts	=E33*MAX(Ship)
52	Amount in WIP	=E34-E35
53	Recycle	0
54	% Scrap	=E38/E34
55	% Waste	=(SUM(E36:E38) + SUM(E46:E50))/E34
56	%WIP	=E52/E34
57	%Good	=E51/E34
58	TOTAL	=SUM(E55:E57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(E7>0,E$36,0)
61	Ext Haz Sub-TPQ	=IF(E8>0,E$36,0)
62	Toxic Chemical	=IF(E9>0,E$36,0)
63	TRI Chemical	=IF(E10>0,E$36,0)
64	SARA H-1	=IF(E11>0,E$36,0)
65	SARA H-2	=IF(E12>0,E$36,0)
66	SARA P-3	=IF(E13>0,E$36,0)
67	SARA P-4	=IF(E14>0,E$36,0)
68	SARA P-5	=IF(E15>0,E$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(E7>0,E$34,0)
71	Ext Haz Sub-TPQ	=IF(E8>0,E$34,0)
72	Toxic Chemical	=IF(E9>0,E$34,0)
73	TRI Chemical	=IF(E10>0,E$34,0)
74	SARA H-1	=IF(E11>0,E$34,0)
75	SARA H-2	=IF(E12>0,E$34,0)
76	SARA P-3	=IF(E13>0,E$34,0)
77	SARA P-4	=IF(E14>0,E$34,0)

29	Inputed by Simulation	Liner Materials
30	Amount Needed /finished part	=G35/MAX(Ship)
31	Avg. lbs needed/week	=G34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	=G18*(1-(G25+G26))/CutParts
34	Amount In	=G18*MandBuff/(1-G20)
35	Amount Out	=SUM(G36:G38)+SUM(G46:G51)
36	Discarded RM's	=G20*G18*MandBuff/(1-G20)
37	Discarded Mat'ls used for Good Parts or WIP	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(G39:G45)
39	Mandrel Prep	=G18*ScrapMP
40	Fil Winding	=G18*ScrapFW
41	Cure	=G18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,IF(ScrapF=ScrapMA+ScrapA+ScrapCut,G18*(ScrapMR-(ScrapFW+ScrapC)),G18*(ScrapMR-(ScrapFW+ScrapC+ScrapMA))),IF(ScrapF=ScrapMA+ScrapA+ScrapCut,G18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC)),G18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC+ScrapMA))))
43	Finishing	=G18*(1-G25)*(ScrapF2)+G33*(1-G26)*(ScrapF3)+G33*(1-(G25+G26))*(ScrapF4)+G18*(ScrapF5)
44	Batch QI	=G33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=G33*ScrapQI
46	Machine Waste	=G25*G18*Mach1
47	Cuttings	=G26*G18*Cut1
48	Waste Resin	0
49	Solvent Bottoms	0
50	Air	0
51	Good Parts	=G33*MAX(Ship)
52	Amount in WIP	=G34-G35
53	Recycle	0
54	% Scrap	=G38/G34
55	% Waste	=(SUM(G36:G38) + SUM(G46:G50))/G34
56	%WIP	=G52/G34
57	%Good	=G51/G34
58	TOTAL	=SUM(G55:G57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(G7>0,G$36,0)
61	Ext Haz Sub-TPQ	=IF(G8>0,G$36,0)
62	Toxic Chemical	=IF(G9>0,G$36,0)
63	TRI Chemical	=IF(G10>0,G$36,0)
64	SARA H-1	=IF(G11>0,G$36,0)
65	SARA H-2	=IF(G12>0,G$36,0)
66	SARA P-3	=IF(G13>0,G$36,0)
67	SARA P-4	=IF(G14>0,G$36,0)
68	SARA P-5	=IF(G15>0,G$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(G7>0,G$34,0)
71	Ext Haz Sub-TPQ	=IF(G8>0,G$34,0)
72	Toxic Chemical	=IF(G9>0,G$34,0)
73	TRI Chemical	=IF(G10>0,G$34,0)
74	SARA H-1	=IF(G11>0,G$34,0)
75	SARA H-2	=IF(G12>0,G$34,0)
76	SARA P-3	=IF(G13>0,G$34,0)

39	Inputed by Simulation	Mandrels	Mandrel Materials
30	Amount Needed /finished part	=I34/MAX(Ship)	=J35/MAX(Ship)
31	Avg. lbs needed/week	=I32*I19	=J34/Weeks
32	Avg # needed/week	=I34/Weeks	N/A
34	Amount in finished part	0	0
35	Amount In	=I27+NewMand	=J18*MandBuff/(1-J20)
36	Amount Out	=NewMand	=SUM(J36:J38)+SUM(J46:J50)
37	Discarded RM's	0	=J20*J18*MandBuff/(1-J20)
38	Discarded Mat'ls used for Good Parts or WIP	=NewMand	=IF(Liner=0,J18*(ScrapMP+ManRem)-J38,J18*ManRem-J38)
39	Discarded Scrap or Mat'ls used for Scrap Parts	0	=SUM(J39:J45)
40	Mandrel Prep	0	=+J18*ScrapMP
41	Fil Winding	0	=J18*ScrapFW
42	Cure	0	=J18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
43	Mandrel Removal	0	=IF(Liner=0,J18*ScrapMR-J40-J18*ScrapC-J18*(ScrapA+ScrapMA+ScrapCut-ScrapF),J18*ScrapMR-J39-J40-J18*ScrapC-J18*(ScrapA+ScrapMA+ScrapCut-ScrapF))
44	Finishing	0	=J18*(ScrapF2+ScrapF5)+J18/CutParts*(ScrapF3+ScrapF4)
45	Batch QI	0	=J18*(ScrapQB+(QIBatch*InspNum))/CutParts
46	Ind QI	0	=J18/CutParts*ScrapQI
47	Machine Waste	0	0
48	Cuttings	0	0
49	Waste Resin	0	0
50	Solvent Bottoms	0	0
51	Air	0	0
52	Good Parts	0	0
53	Amount in WIP	=I34-I35	=IF(Liner=0,J18*(MandBuff-(ScrapMP+ManRem)),J18*(MandBuff-ManRem))
54	Recycle	0	0
55	% Scrap	=I38/I34	=J38/J34
56	% Waste	=(SUM(I36:I38) + SUM(I46:I50))/I34	=(SUM(J36:J38) + SUM(J46:J50))/J34
57	%WIP	=I52/I34	=J52/J34
58	%Good	=I51/I34	=J51/J34
59	TOTAL	=SUM(I55:I57)	=SUM(J55:J57)
60	WasteCategories		
61	Ext Haz Sub-Rep Quantity	=IF(I7>0,I$36*MandrelWeight,0)	=IF(J7>0,J$36,0)
62	Ext Haz Sub-TPQ	=IF(I8>0,I$36*MandrelWeight,0)	=IF(J8>0,J$36,0)
63	Toxic Chemical	=IF(I9>0,I$36*MandrelWeight,0)	=IF(J9>0,J$36,0)
64	TRI Chemical	=IF(I10>0,I$36*MandrelWeight,0)	=IF(J10>0,J$36,0)
65	SARA H-1	=IF(I11>0,I$36*MandrelWeight,0)	=IF(J11>0,J$36,0)
66	SARA H-2	=IF(I12>0,I$36*MandrelWeight,0)	=IF(J12>0,J$36,0)
67	SARA P-3	=IF(I13>0,I$36*MandrelWeight,0)	=IF(J13>0,J$36,0)
68	SARA P-4	=IF(I14>0,I$36*MandrelWeight,0)	=IF(J14>0,J$36,0)
69	SARA P-5	=IF(I15>0,I$36*MandrelWeight,0)	=IF(J15>0,J$36,0)
70	Usage Categories		
71	Ext Haz Sub-Rep Quantity	=IF(I7>0,I$34,0)	=IF(J7>0,J$34,0)

72	Ext Haz Sub-TPQ	=IF(I8>0,I$34,0)	=IF(J8>0,J$34,0)
73	Toxic Chemical	=IF(I9>0,I$34,0)	=IF(J9>0,J$34,0)
74	TRI Chemical	=IF(I10>0,I$34,0)	=IF(J10>0,J$34,0)
75	SARA H-1	=IF(I11>0,I$34,0)	=IF(J11>0,J$34,0)
76	SARA H-2	=IF(I12>0,I$34,0)	=IF(J12>0,J$34,0)
77	SARA P-3	=IF(I13>0,I$34,0)	=IF(J13>0,J$34,0)
78	SARA P-4	=IF(I14>0,I$34,0)	=IF(J14>0,J$34,0)
	SARA P-5	=IF(I15>0,I$34,0)	=IF(J15>0,J$34,0)

29	Inputed by Simulation	Resin
30	Amount Needed /finished part	=L35/MAX(Ship)
31	Avg. lbs needed/week	=L34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	=L18*(1-(L25+L26))/CutParts
34	Amount In	=L18*FWBatch*FilWind1+L36+L48+L49
35	Amount Out	=SUM(L36:L38)+SUM(L46:L51)
36	Discarded RM's	=L20*((L18*FWBatch*FilWind1)+L48+L49)/(1-L20)
37	Discarded Mat'ls used for Good Parts or WIP	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(L39:L45)
39	Mandrel Prep	0
40	Fil Winding	=L18*ScrapFW
41	Cure	=L18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,IF(ScrapF=ScrapMA+ScrapA+ScrapCut,L18*(ScrapMR-(ScrapFW+ScrapC)),L18*(ScrapMR-(ScrapFW+ScrapC+(1-L25)*ScrapMA))),IF(ScrapF=ScrapMA+ScrapA+ScrapCut,L18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC)),L18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC+(1-L25)*ScrapMA))))
43	Finishing	=L18*(1-L25)*(ScrapF2)+L18*((1-L26)/CutParts)*(ScrapF3)+L33*(ScrapF4)+L18*(ScrapF5)
44	Batch QI	=L33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=L33*ScrapQI
46	Machine Waste	=L25*L18*Mach1
47	Cuttings	=L26*L18*Cut1
48	Waste Resin	=L22*L18*FWBatch*FilWind1/(1-L22)
49	Solvent Bottoms	=L23*L18*FWBatch*FilWind1/(1-L23)
50	Air	0
51	Good Parts	=L33*MAX(Ship)
52	Amount in WIP	=L34-L35
53	Recycle	0
54	% Scrap	=L38/L34
55	% Waste	=(SUM(L36:L38) + SUM(L46:L50))/L34
56	%WIP	=L52/L34
57	%Good	=L51/L34
58	TOTAL	=SUM(L55:L57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(L7>0,L$36,0)
61	Ext Haz Sub-TPQ	=IF(L8>0,L$36,0)
62	Toxic Chemical	=IF(L9>0,L$36,0)
63	TRI Chemical	=IF(L10>0,L$36,0)
64	SARA H-1	=IF(L11>0,L$36,0)
65	SARA H-2	=IF(L12>0,L$36,0)
66	SARA P-3	=IF(L13>0,L$36,0)
67	SARA P-4	=IF(L14>0,L$36,0)
68	SARA P-5	=IF(L15>0,L$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(L7>0,L$34,0)
71	Ext Haz Sub-TPQ	=IF(L8>0,L$34,0)
72	Toxic Chemical	=IF(L9>0,L$34,0)
73	TRI Chemical	=IF(L10>0,L$34,0)
74	SARA H-1	=IF(L11>0,L$34,0)
75	SARA H-2	=IF(L12>0,L$34,0)
76	SARA P-3	=IF(L13>0,L$34,0)
77	SARA P-4	=IF(L14>0,L$34,0)
78	SARA P-5	=IF(L15>0,L$34,0)

29	Inputed by Simulation	Fibers
30	Amount Needed /finished part	=M35/MAX(Ship)
31	Avg. lbs needed/week	=M34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	=M18*(1-(M25+M26))/CutParts
34	Amount In	=M18*FWBatch*FilWind1+M36+M48+M49
35	Amount Out	=SUM(M36:M38)+SUM(M46:M51)
36	Discarded RM's	=M20*((M18*FWBatch*FilWind1)+M48+M49)/(1-M20)
37	Discarded Mat'ls used for Good Parts or WIP	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(M39:M45)
39	Mandrel Prep	0
40	Fil Winding	=M18*ScrapFW
41	Cure	=M18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,IF(ScrapF=ScrapMA+ScrapA+ScrapCut,M18*(ScrapMR-(ScrapFW+ScrapC)),M18*(ScrapMR-(ScrapFW+ScrapC+(1-M25)*ScrapMA))),IF(ScrapF=ScrapMA+ScrapA+ScrapCut,M18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC)),M18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC+(1-M25)*ScrapMA))))
43	Finishing	=M18*(1-M25)*(ScrapF2)+M18*((1-M26)/CutParts)*(ScrapF3)+M33*(ScrapF4)+M18*(ScrapF5)
44	Batch QI	=M33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=M33*ScrapQI
46	Machine Waste	=M25*M18*Mach1
47	Cuttings	=M26*M18*Cut1
48	Waste Resin	=M22*M18*FWBatch*FilWind1/(1-M22)
49	Solvent Bottoms	=M23*M18*FWBatch*FilWind1/(1-M23)
50	Air	0
51	Good Parts	=M33*MAX(Ship)
52	Amount in WIP	=M34-M35
53	Recycle	0
54	% Scrap	=M38/M34
55	% Waste	=(SUM(M36:M38) + SUM(M46:M50))/M34
56	%WIP	=M52/M34
57	%Good	=M51/M34
58	TOTAL	=SUM(M55:M57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(M7>0,M$36,0)
61	Ext Haz Sub-TPQ	=IF(M8>0,M$36,0)
62	Toxic Chemical	=IF(M9>0,M$36,0)
63	TRI Chemical	=IF(M10>0,M$36,0)
64	SARA H-1	=IF(M11>0,M$36,0)
65	SARA H-2	=IF(M12>0,M$36,0)
66	SARA P-3	=IF(M13>0,M$36,0)
67	SARA P-4	=IF(M14>0,M$36,0)
68	SARA P-5	=IF(M15>0,M$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(M7>0,M$34,0)
71	Ext Haz Sub-TPQ	=IF(M8>0,M$34,0)
72	Toxic Chemical	=IF(M9>0,M$34,0)
73	TRI Chemical	=IF(M10>0,M$34,0)
74	SARA H-1	=IF(M11>0,M$34,0)
75	SARA H-2	=IF(M12>0,M$34,0)
76	SARA P-3	=IF(M13>0,M$34,0)
77	SARA P-4	=IF(M14>0,M$34,0)

29	Inputed by Simulation	Additives
30	Amount Needed /finished part	=O35/MAX(Ship)
31	Avg. lbs needed/week	=O34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	=O18*(1-(O25+O26))/CutParts
34	Amount In	=O18*FWBatch*FilWind1+O36+O48+O49
35	Amount Out	=SUM(O36:O38)+SUM(O46:O51)
36	Discarded RM's	=O20*((O18*FWBatch*FilWind1)+O48+O49)/(1-O20)
37	Discarded Mat'ls used for Good Parts or WIP	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(O39:O45)
39	Mandrel Prep	0
40	Fil Winding	=O18*ScrapFW
41	Cure	=O18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,IF(ScrapF=ScrapMA+ScrapA+ScrapCut,O18*(ScrapMR-(ScrapFW+ScrapC)),O18*(ScrapMR-(ScrapFW+ScrapC+(1-O25)*ScrapMA))),IF(ScrapF=ScrapMA+ScrapA+ScrapCut,O18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC)),O18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC+(1-O25)*ScrapMA))))
43	Finishing	=O18*(1-O25)*(ScrapF2)+O18*((1-O26)/CutParts)*(ScrapF3)+O33*(ScrapF4)+O18*(ScrapF5)
44	Batch QI	=O33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=O33*ScrapQI
46	Machine Waste	=O25*O18*Mach1
47	Cuttings	=O26*O18*Cut1
48	Waste Resin	=O22*O18*FWBatch*FilWind1/(1-O22)
49	Solvent Bottoms	=O23*O18*FWBatch*FilWind1/(1-O23)
50	Air	0
51	Good Parts	=O33*MAX(Ship)
52	Amount in WIP	=O34-O35
53	Recycle	0
54	% Scrap	=O38/O34
55	% Waste	=(SUM(O36:O38) + SUM(O46:O50))/O34
56	%WIP	=O52/O34
57	%Good	=O51/O34
58	TOTAL	=SUM(O55:O57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(O7>0,O$36,0)
61	Ext Haz Sub-TPQ	=IF(O8>0,O$36,0)
62	Toxic Chemical	=IF(O9>0,O$36,0)
63	TRI Chemical	=IF(O10>0,O$36,0)
64	SARA H-1	=IF(O11>0,O$36,0)
65	SARA H-2	=IF(O12>0,O$36,0)
66	SARA P-3	=IF(O13>0,O$36,0)
67	SARA P-4	=IF(O14>0,O$36,0)
68	SARA P-5	=IF(O15>0,O$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(O7>0,O$34,0)
71	Ext Haz Sub-TPQ	=IF(O8>0,O$34,0)
72	Toxic Chemical	=IF(O9>0,O$34,0)
73	TRI Chemical	=IF(O10>0,O$34,0)
74	SARA H-1	=IF(O11>0,O$34,0)
75	SARA H-2	=IF(O12>0,O$34,0)
76	SARA P-3	=IF(O13>0,O$34,0)
77	SARA P-4	=IF(O14>0,O$34,0)

29	Inputed by Simulation	Curing Agent
30	Amount Needed /finished part	=Q35/MAX(Ship)
31	Avg. lbs needed/week	=Q34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	=Q18*(1-(Q25+Q26))/CutParts
34	Amount In	=Q18*FWBatch*FilWind1+Q36+Q48+Q49
35	Amount Out	=SUM(Q36:Q38)+SUM(Q46:Q51)
36	Discarded RM's	=Q20*((Q18*FWBatch*FilWind1)+Q48+Q49)/(1-Q20)
37	Discarded Mat'ls used for Good Parts or WIP	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(Q39:Q45)
39	Mandrel Prep	0
40	Fil Winding	=Q18*ScrapFW
41	Cure	=Q18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,IF(ScrapF=ScrapMA+ScrapA+ScrapCut,Q18*(ScrapMR-(ScrapFW+ScrapC)),Q18*(ScrapMR-(ScrapFW+ScrapC+(1-Q25)*ScrapMA))),IF(ScrapF=ScrapMA+ScrapA+ScrapCut,Q18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC)),Q18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC+(1-Q25)*ScrapMA))))
43	Finishing	=Q18*(1-Q25)*(ScrapF2)+Q18*((1-Q26)/CutParts)*(ScrapF3)+Q33*(ScrapF4)+Q18*(ScrapF5)
44	Batch QI	=Q33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=Q33*ScrapQI
46	Machine Waste	=Q25*Q18*Mach1
47	Cuttings	=Q26*Q18*Cut1
48	Waste Resin	=Q22*Q18*FWBatch*FilWind1/(1-Q22)
49	Solvent Bottoms	=Q23*Q18*FWBatch*FilWind1/(1-Q23)
50	Air	0
51	Good Parts	=Q33*MAX(Ship)
52	Amount in WIP	=Q34-Q35
53	Recycle	0
54	% Scrap	=Q38/Q34
55	% Waste	=(SUM(Q36:Q38) + SUM(Q46:Q50))/Q34
56	%WIP	=Q52/Q34
57	%Good	=Q51/Q34
58	TOTAL	=SUM(Q55:Q57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(Q7>0,Q$36,0)
61	Ext Haz Sub-TPQ	=IF(Q8>0,Q$36,0)
62	Toxic Chemical	=IF(Q9>0,Q$36,0)
63	TRI Chemical	=IF(Q10>0,Q$36,0)
64	SARA H-1	=IF(Q11>0,Q$36,0)
65	SARA H-2	=IF(Q12>0,Q$36,0)
66	SARA P-3	=IF(Q13>0,Q$36,0)
67	SARA P-4	=IF(Q14>0,Q$36,0)
68	SARA P-5	=IF(Q15>0,Q$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(Q7>0,Q$34,0)
71	Ext Haz Sub-TPQ	=IF(Q8>0,Q$34,0)
72	Toxic Chemical	=IF(Q9>0,Q$34,0)
73	TRI Chemical	=IF(Q10>0,Q$34,0)
74	SARA H-1	=IF(Q11>0,Q$34,0)
75	SARA H-2	=IF(Q12>0,Q$34,0)
76	SARA P-3	=IF(Q13>0,Q$34,0)

29	Inputed by Simulation	Prepreg
30	Amount Needed /finished part	=R35/MAX(Ship)
31	Avg. lbs needed/week	=R34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	=R18*(1-(R25+R26))/CutParts
34	Amount In	=R18*FWBatch*FilWind1+R36+R48+R49
35	Amount Out	=SUM(R36:R38)+SUM(R46:R51)
36	Discarded RM's	=R20*((R18*FWBatch*FilWind1)+R48+R49)/(1-R20)
37	Discarded Mat'ls used for Good Parts or WIP	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(R39:R45)
39	Mandrel Prep	0
40	Fil Winding	=R18*ScrapFW
41	Cure	=R18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,IF(ScrapF=ScrapMA+ScrapA+ScrapCut,R18*(ScrapMR-(ScrapFW+ScrapC)),R18*(ScrapMR-(ScrapFW+ScrapC+(1-R25)*ScrapMA))),IF(ScrapF=ScrapMA+ScrapA+ScrapCut,R18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC)),R18*(ScrapMR-(ScrapMP+ScrapFW+ScrapC+(1-R25)*ScrapMA))))
43	Finishing	=R18*(1-R25)*(ScrapF2)+R18*((1-R26)/CutParts)*(ScrapF3)+R33*(ScrapF4)+R18*(ScrapF5)
44	Batch QI	=R33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=R33*ScrapQI
46	Machine Waste	=R25*R18*Mach1
47	Cuttings	=R26*R18*Cut1
48	Waste Resin	=R22*R18*FWBatch*FilWind1/(1-R22)
49	Solvent Bottoms	=R23*R18*FWBatch*FilWind1/(1-R23)
50	Air	0
51	Good Parts	=R33*MAX(Ship)
52	Amount in WIP	=R34-R35
53	Recycle	0
54	% Scrap	=R38/R34
55	% Waste	=(SUM(R36:R38) + SUM(R46:R50))/R34
56	%WIP	=R52/R34
57	%Good	=R51/R34
58	TOTAL	=SUM(R55:R57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(R7>0,R$36,0)
61	Ext Haz Sub-TPQ	=IF(R8>0,R$36,0)
62	Toxic Chemical	=IF(R9>0,R$36,0)
63	TRI Chemical	=IF(R10>0,R$36,0)
64	SARA H-1	=IF(R11>0,R$36,0)
65	SARA H-2	=IF(R12>0,R$36,0)
66	SARA P-3	=IF(R13>0,R$36,0)
67	SARA P-4	=IF(R14>0,R$36,0)
68	SARA P-5	=IF(R15>0,R$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(R7>0,R$34,0)
71	Ext Haz Sub-TPQ	=IF(R8>0,R$34,0)
72	Toxic Chemical	=IF(R9>0,R$34,0)
73	TRI Chemical	=IF(R10>0,R$34,0)
74	SARA H-1	=IF(R11>0,R$34,0)
75	SARA H-2	=IF(R12>0,R$34,0)
76	SARA P-3	=IF(R13>0,R$34,0)
77	SARA P-4	=IF(R14>0,R$34,0)

29	Inputed by Simulation	Mandrel Prep Solvent
30	Amount Needed /finished part	=S35/MAX(Ship)
31	Avg. lbs needed/week	=S34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	0
34	Amount In	=+(1-S21)*S18*MandBuff
35	Amount Out	=SUM(S49:S50)
36	Discarded RM's	0
37	Discarded Mat'ls used for Good Parts or WIP	=S34-S38
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(S39:S45)
39	Mandrel Prep	=+(1-S21)*S18*ScrapMP
40	Fil Winding	=(1-S21)*S18*ScrapFW
41	Cure	=(1-S21)*S18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,S18*ScrapMR-S40-S18*ScrapC-S18*(ScrapA+ScrapMA+ScrapCut-ScrapF),S18*ScrapMR-S39-S40-S18*ScrapC-S18*(ScrapA+ScrapMA+ScrapCut-ScrapF))*(1-S21)
43	Finishing	=(S18*(ScrapF2+ScrapF5)+S18/CutParts*(ScrapF3+ScrapF4))*(1-S21)
44	Batch QI	=(1-S21)*S18*(ScrapQB+(QIBatch*InspNum))/CutParts
45	Ind QI	=(1-S21)*S18/CutParts*ScrapQI
46	Machine Waste	0
47	Cuttings	0
48	Waste Resin	0
49	Solvent Bottoms	=S18*MandBuff*S23
50	Air	=S18*MandBuff*S24
51	Good Parts	0
52	Amount in WIP	0
53	Recycle	=S18*MandBuff*S21
54	% Scrap	=S38/S34
55	% Waste	=(S49+S50)/S34
56	%WIP	0
57	%Good	=S51/S34
58	TOTAL	=SUM(S55:S57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(S7>0,S$36,0)
61	Ext Haz Sub-TPQ	=IF(S8>0,S$36,0)
62	Toxic Chemical	=IF(S9>0,S$36,0)
63	TRI Chemical	=IF(S10>0,S$36,0)
64	SARA H-1	=IF(S11>0,S$36,0)
65	SARA H-2	=IF(S12>0,S$36,0)
66	SARA P-3	=IF(S13>0,S$36,0)
67	SARA P-4	=IF(S14>0,S$36,0)
68	SARA P-5	=IF(S15>0,S$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(S7>0,S$34,0)
71	Ext Haz Sub-TPQ	=IF(S8>0,S$34,0)
72	Toxic Chemical	=IF(S9>0,S$34,0)
73	TRI Chemical	=IF(S10>0,S$34,0)
74	SARA H-1	=IF(S11>0,S$34,0)
75	SARA H-2	=IF(S12>0,S$34,0)
76	SARA P-3	=IF(S13>0,S$34,0)
77	SARA P-4	=IF(S14>0,S$34,0)
78	SARA P-5	=IF(S15>0,S$34,0)

29	Inputed by Simulation	Solvent 1 (Filament Winding)	Solvent 2 (Filament Winding)
30	Amount Needed /finished part	=Solv1/MAX(Ship)	=Solv2/MAX(Ship)
31	Avg. lbs needed/week	=Solv1/Weeks	=Solv2/Weeks
32	Avg # needed/week	N/A	N/A
33	Amount in finished part	0	0
34	Amount In	=(1-T21)*Solv1	=(1-U21)*Solv2
35	Amount Out	=SUM(T49:T50)	=SUM(U49:U50)
36	Discarded RM's	0	0
37	Discarded Mat'ls used for Good Parts or WIP	0	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(T39:T45)	=SUM(U39:U45)
39	Mandrel Prep	0	0
40	Fil Winding	=(1-T21)*Solv1*ScrapFW/(FWBatch*FilWind1)	=(1-T21)*Solv2*ScrapFW/(FWBatch*FilWind1)
41	Cure	0	0
42	Mandrel Removal	0	0
43	Finishing	0	0
44	Batch QI	0	0
45	Ind QI	0	0
46	Machine Waste	0	0
47	Cuttings	0	0
48	Waste Resin	0	0
49	Solvent Bottoms	=Solv1*T23	=Solv2*U23
50	Air	=Solv1*T24	=Solv2*U24
51	Good Parts	0	0
52	Amount in WIP	0	0
53	Recycle	=T34*T21	=U34*U21
54	% Scrap	=T38/T34	=U38/U34
55	% Waste	=(T49+T50)/T34	=(U49+U50)/U34
56	%WIP	0	0
57	%Good	=T51/T34	=U51/U34
58	TOTAL	=SUM(T55:T57)	=SUM(U55:U57)
59	WasteCategories		
60	Ext Haz Sub-Rep Quantity	=IF(T7>0,T$36,0)	=IF(U7>0,U$36,0)
61	Ext Haz Sub-TPQ	=IF(T8>0,T$36,0)	=IF(U8>0,U$36,0)
62	Toxic Chemical	=IF(T9>0,T$36,0)	=IF(U9>0,U$36,0)
63	TRI Chemical	=IF(T10>0,T$36,0)	=IF(U10>0,U$36,0)
64	SARA H-1	=IF(T11>0,T$36,0)	=IF(U11>0,U$36,0)
65	SARA H-2	=IF(T12>0,T$36,0)	=IF(U12>0,U$36,0)
66	SARA P-3	=IF(T13>0,T$36,0)	=IF(U13>0,U$36,0)
67	SARA P-4	=IF(T14>0,T$36,0)	=IF(U14>0,U$36,0)
68	SARA P-5	=IF(T15>0,T$36,0)	=IF(U15>0,U$36,0)
69	Usage Categories		
70	Ext Haz Sub-Rep Quantity	=IF(T7>0,T$34,0)	=IF(U7>0,U$34,0)
71	Ext Haz Sub-TPQ	=IF(T8>0,T$34,0)	=IF(U8>0,U$34,0)
72	Toxic Chemical	=IF(T9>0,T$34,0)	=IF(U9>0,U$34,0)
73	TRI Chemical	=IF(T10>0,T$34,0)	=IF(U10>0,U$34,0)
74	SARA H-1	=IF(T11>0,T$34,0)	=IF(U11>0,U$34,0)
75	SARA H-2	=IF(T12>0,T$34,0)	=IF(U12>0,U$34,0)
76	SARA P-3	=IF(T13>0,T$34,0)	=IF(U13>0,U$34,0)
77	SARA P-4	=IF(T14>0,T$34,0)	=IF(U14>0,U$34,0)
78	SARA P-5	=IF(T15>0,T$34,0)	=IF(U15>0,U$34,0)

29	Inputed by Simulation	Mandrel Removal Solvent
30	Amount Needed /finished part	=V35/MAX(Ship)
31	Avg. lbs needed/week	=V34/Weeks
32	Avg # needed/week	N/A
33	Amount in finished part	0
34	Amount In	=+(1-V21)*V18*ManRem
35	Amount Out	=SUM(V49:V50)
36	Discarded RM's	0
37	Discarded Mat'ls used for Good Parts or WIP	=V34-V38
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(V39:V45)
39	Mandrel Prep	=+(1-V21)*V18*ScrapMP
40	Fil Winding	=(1-V21)*V18*ScrapFW
41	Cure	=(1-V21)*V18*(ScrapC1+ScrapC2+ScrapC3+ScrapC4)
42	Mandrel Removal	=IF(Liner=0,V18*ScrapMR-V40-V18*ScrapC-V18*(ScrapA+ScrapMA+ScrapCut-ScrapF),V18*ScrapMR-V39-V40-V18*ScrapC-V18*(ScrapA+ScrapMA+ScrapCut-ScrapF))*(1-V21)
43	Finishing	=IF(ScrapF=ScrapMA+ScrapA+ScrapCut,V18*(ScrapF2+ScrapF5)+V18/CutParts*(ScrapF3+ScrapF4),IF(AND(ScrapA=0,ScrapCut>0),V18/CutParts*(ScrapCut),IF(AND(ScrapA>0,ScrapCut=0),V18*(ScrapA),IF(AND(ScrapF1>0,ScrapF0=0),V18/CutParts*(ScrapCut+ScrapA),IF(AND(ScrapF1>0,ScrapF0>0),V18*(ScrapA)+V18/CutParts*(ScrapCut),0)))))*(1-V21)
44	Batch QI	=(1-V21)*V18*(ScrapQB+(QIBatch*InspNum))/CutParts
45	Ind QI	=(1-V21)*V18/CutParts*ScrapQI
46	Machine Waste	0
47	Cuttings	0
48	Waste Resin	0
49	Solvent Bottoms	=V23*V18*ManRem
50	Air	=V24*V18*ManRem
51	Good Parts	0
52	Amount in WIP	0
53	Recycle	=V18*ManRem*V21
54	% Scrap	=V38/V34
55	% Waste	=(V49+V50)/V34
56	%WIP	0
57	%Good	=V51/V34
58	TOTAL	=SUM(V55:V57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(V7>0,V$36,0)
61	Ext Haz Sub-TPQ	=IF(V8>0,V$36,0)
62	Toxic Chemical	=IF(V9>0,V$36,0)
63	TRI Chemical	=IF(V10>0,V$36,0)
64	SARA H-1	=IF(V11>0,V$36,0)
65	SARA H-2	=IF(V12>0,V$36,0)
66	SARA P-3	=IF(V13>0,V$36,0)
67	SARA P-4	=IF(V14>0,V$36,0)
68	SARA P-5	=IF(V15>0,V$36,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(V7>0,V$34,0)
71	Ext Haz Sub-TPQ	=IF(V8>0,V$34,0)
72	Toxic Chemical	=IF(V9>0,V$34,0)
73	TRI Chemical	=IF(V10>0,V$34,0)
74	SARA H-1	=IF(V11>0,V$34,0)
75	SARA H-2	=IF(V12>0,V$34,0)
76	SARA P-3	=IF(V13>0,V$34,0)
77	SARA P-4	=IF(V14>0,V$34,0)
78	SARA P-5	=IF(V15>0,V$34,0)

29	Inputed by Simulation	Bag Materials
30	Amount Needed /finished part	=W34/MAX(Ship)
31	Avg. lbs needed/week	=W32*W19
32	Avg # needed/week	=W34/Weeks
33	Amount in finished part	0
34	Amount In	=IF(W28=1,BuffC3*W18+W36,NewBags+W27)
35	Amount Out	=IF(W28=1,W18*Cure3*BatchC3 + W36,NewBags)
36	Discarded RM's	=W20*W18*BuffC3/(1-W20)
37	Discarded Mat'ls used for Good Parts or WIP	=IF(W28=1,W18*Cure3*BatchC3-W38,NewBags)
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(W39:W45)
39	Mandrel Prep	0
40	Fil Winding	0
41	Cure	=IF(W28=1,IF(OrderC3=1,(ScrapC1+ScrapC2+ScrapC3+ScrapC4)*W18,ScrapC3*W18),0)
42	Mandrel Removal	=IF(W28=1,IF(OrderC3=1,IF(Liner=0,W18*ScrapMR-W40-W18*ScrapC-W18*(ScrapA+ScrapMA+ScrapCut-ScrapF),W18*ScrapMR-W39-W40-W18*ScrapC-W18*(ScrapA+ScrapMA+ScrapCut-ScrapF)),0),0)
43	Finishing	=IF(W28=1,IF(OR(ScrapF=ScrapMA+ScrapA+ScrapCut,OrderC3=1),W18*(ScrapF2+ScrapF5)+W18/CutParts*(ScrapF3+ScrapF4),IF(AND(ScrapA=0,ScrapCut>0),W18/CutParts*(ScrapCut),IF(AND(ScrapA>0,ScrapCut=0),W18*(ScrapA),IF(AND(ScrapF1>0,ScrapF0=0),W18/CutParts*(ScrapCut+ScrapA),IF(AND(ScrapF1>0,ScrapF0>0),W18*(ScrapA)+W18/CutParts*(ScrapCut),0)))))),0)
44	Batch QI	=IF(W28=1,W18*(ScrapQB+(QIBatch*InspNum))/CutParts,0)
45	Ind QI	=IF(W28=1,W18/CutParts*ScrapQI,0)
46	Machine Waste	0
47	Cuttings	0
48	Waste Resin	0
49	Solvent Bottoms	0
50	Air	0
51	Good Parts	0
52	Amount in WIP	=W34-W35
53	Recycle	0
54	% Scrap	=W38/W34
55	% Waste	=(SUM(W36:W38) + SUM(W46:W50))/W34
56	%WIP	=W52/W34
57	%Good	=W51/W34
58	TOTAL	=SUM(W55:W57)
59	WasteCategories	
60	Ext Haz Sub-Rep Quantity	=IF(W7>0,W$36*BagWeight,0)
61	Ext Haz Sub-TPQ	=IF(W8>0,W$36*BagWeight,0)
62	Toxic Chemical	=IF(W9>0,W$36*BagWeight,0)
63	TRI Chemical	=IF(W10>0,W$36*BagWeight,0)
64	SARA H-1	=IF(W11>0,W$36*BagWeight,0)
65	SARA H-2	=IF(W12>0,W$36*BagWeight,0)
66	SARA P-3	=IF(W13>0,W$36*BagWeight,0)
67	SARA P-4	=IF(W14>0,W$36*BagWeight,0)
68	SARA P-5	=IF(W15>0,W$36*BagWeight,0)
69	Usage Categories	
70	Ext Haz Sub-Rep Quantity	=IF(W7>0,W$34,0)
71	Ext Haz Sub-TPQ	=IF(W8>0,W$34,0)
72	Toxic Chemical	=IF(W9>0,W$34,0)
73	TRI Chemical	=IF(W10>0,W$34,0)
74	SARA H-1	=IF(W11>0,W$34,0)
75	SARA H-2	=IF(W12>0,W$34,0)
76	SARA P-3	=IF(W13>0,W$34,0)
77	SARA P-4	=IF(W14>0,W$34,0)
78	SARA P-5	=IF(W15>0,W$34,0)

29	Inputed by Simulation	Assembly Parts	Assembly Materials
30	Amount Needed /finished part	=X35/MAX(Ship)	=Z35/MAX(Ship)
31	Avg. lbs needed/week	=X34/Weeks	=Z32*Z19
32	Avg # needed/week	N/A	=Z34/Weeks
33	Amount in finished part	=IF(ScrapF0=0,X18,X18/2)	=IF(ScrapF0=0,Z18,Z18/2)
34	Amount In	=+X18*Assem1+X36	=+Z18*Assem1+Z36
35	Amount Out	=SUM(X36:X38)+SUM(X46:X51)	=SUM(Z36:Z38)+SUM(Z46:Z51)
36	Discarded RM's	=X20*X18*Assem1/(1-X20)	=Z20*Z18*Assem1/(1-Z20)
37	Discarded Mat'ls used for Good Parts or WIP	0	0
38	Discarded Scrap or Mat'ls used for Scrap Parts	=SUM(X39:X45)	=SUM(Z39:Z45)
39	Mandrel Prep	0	0
40	Fil Winding	0	0
41	Cure	0	0
42	Mandrel Removal	0	0
43	Finishing	=X18*ScrapF1+(X18/CutParts)*ScrapF0	=Z18*ScrapF1+(Z18/CutParts)*ScrapF0
44	Batch QI	=X33*(ScrapQB+QIBatch*InspNum)	=Z33*(ScrapQB+QIBatch*InspNum)
45	Ind QI	=X33*ScrapQI	=Z33*ScrapQI
46	Machine Waste	0	0
47	Cuttings	0	0
48	Waste Resin	0	0
49	Solvent Bottoms	0	0
50	Air	0	0
51	Good Parts	=IF(ScrapF0=0,MAX(Ship)*X18,MAX(Ship)*(X18/CutParts))	=IF(ScrapF0=0,MAX(Ship)*Z18,MAX(Ship)*(Z18/CutParts))
52	Amount in WIP	=X34-X35	=Z34-Z35
53	Recycle	0	0
54	% Scrap	=X38/X34	=Z38/Z34
55	% Waste	=(SUM(X36:X38) + SUM(X46:X50))/X34	=(SUM(Z36:Z38) + SUM(Z46:Z50))/Z34
56	%WIP	=X52/X34	=Z52/Z34
57	%Good	=X51/X34	=Z51/Z34
58	TOTAL	=SUM(X55:X57)	=SUM(Z55:Z57)
59	WasteCategories		
60	Ext Haz Sub-Rep Quantity	=IF(X7>0,X$36,0)	=IF(Z7>0,Z$36*APPart1Weight,0)
61	Ext Haz Sub-TPQ	=IF(X8>0,X$36,0)	=IF(Z8>0,Z$36*APPart1Weight,0)
62	Toxic Chemical	=IF(X9>0,X$36,0)	=IF(Z9>0,Z$36*APPart1Weight,0)
63	TRI Chemical	=IF(X10>0,X$36,0)	=IF(Z10>0,Z$36*APPart1Weight,0)
64	SARA H-1	=IF(X11>0,X$36,0)	=IF(Z11>0,Z$36*APPart1Weight,0)
65	SARA H-2	=IF(X12>0,X$36,0)	=IF(Z12>0,Z$36*APPart1Weight,0)
66	SARA P-3	=IF(X13>0,X$36,0)	=IF(Z13>0,Z$36*APPart1Weight,0)
67	SARA P-4	=IF(X14>0,X$36,0)	=IF(Z14>0,Z$36*APPart1Weight,0)
68	SARA P-5	=IF(X15>0,X$36,0)	=IF(Z15>0,Z$36*APPart1Weight,0)
69	Usage Categories		
70	Ext Haz Sub-Rep Quantity	=IF(X7>0,X$34,0)	=IF(Z7>0,Z$34,0)
71	Ext Haz Sub-TPQ	=IF(X8>0,X$34,0)	=IF(Z8>0,Z$34,0)
72	Toxic Chemical	=IF(X9>0,X$34,0)	=IF(Z9>0,Z$34,0)
73	TRI Chemical	=IF(X10>0,X$34,0)	=IF(Z10>0,Z$34,0)
74	SARA H-1	=IF(X11>0,X$34,0)	=IF(Z11>0,Z$34,0)
75	SARA H-2	=IF(X12>0,X$34,0)	=IF(Z12>0,Z$34,0)
76	SARA P-3	=IF(X13>0,X$34,0)	=IF(Z13>0,Z$34,0)
77	SARA P-4	=IF(X14>0,X$34,0)	=IF(Z14>0,Z$34,0)
78	SARA P-5	=IF(X15>0,X$34,0)	=IF(Z15>0,Z$34,0)

Environmental Database	Wt/Finished part
Waste Type	Avg
Discarded RM's	=SUM(Sheet2!B36,Sheet2!E36,Sheet2!F36,Sheet2!G36,Sheet2!H36,Sheet2!J36:Sheet2!V36,Sheet2!X36,Sheet2!Y36,Sheet2!C36*MPPart1Weight,Sheet2!D36*MPPart2Weight,Sheet2!W36*BagWeight,Sheet2!Z36*APart1Weight,Sheet2!AA36*APart2Weight,Sheet2!AB36*APart3Weight,Sheet2!AC36*APart4Weight)/MAX(Ship)
Total Amount of Mat'l in Scrap	=TotalScrap_part
Machine Waste	=SUM(MachineWaste)/MAX(Ship)
Cuttings	=SUM(Cuttings)/MAX(Ship)
Waste Resin	=SUM(WasteResin)/MAX(Ship)
Solvent Bottoms	=SUM(SolventBottoms)/MAX(Ship)
Air	=SUM(Air)/MAX(Ship)
Discarded Mat'ls used for good parts or WIP	=SUM(B11:B14)
Mandrel Mat'ls	=SUM(DiscardedMMatls)/MAX(Ship)
Bag Mat'ls	=DiscardedBags*BagWeight/MAX(Ship)
Mold Release	=DiscardedMR/MAX(Ship)
Mandrels	=DiscardedMandrels*MandrelWeight/MAX(Ship)
Total	=SUM(B3:B10)
Environmental Categories	Waste/Finished Part
Ext Haz Sub-Rep Quantity	=SUM(Ext_Haz_Sub_Rep_Quantity)/MAX(Ship)
Ext Haz Sub-TPQ	=SUM(Ext_Haz_Sub_TPQ)/MAX(Ship)
Toxic Chemical	=SUM(Toxic_Chemical)/MAX(Ship)
TRI Chemical	=SUM(TRI_Chemical)/MAX(Ship)
SARA H-1	=SUM(SARAH1)/MAX(Ship)
SARA H-2	=SUM(SARAH2)/MAX(Ship)
SARA P-3	=SUM(SARAP3)/MAX(Ship)
SARA P-4	=SUM(SARAP4)/MAX(Ship)
SARA P-5	=SUM(SARAP5)/MAX(Ship)

Environmental Database	Wt/Week
Waste Type	Avg
Discarded RM's	=SUM(DiscardedRM)/Weeks
Total Amount of Mat'l in Scrap	=TotalScrap Week
Machine Waste	=SUM(MachineWaste)/Weeks
Cuttings	=SUM(Cuttings)/Weeks
Waste Resin	=SUM(WasteResin)/Weeks
Solvent Bottoms	=SUM(SolventBottoms)/Weeks
Air	=SUM(Air)/Weeks
Discarded Mat'ls used for good parts or WIP	=SUM(D11:D14)
Mandrel Mat'ls	=SUM(DiscardedMMatls)/Weeks
Bag Mat'ls	=DiscardedBags*BagWeight/Weeks
Mold Release	=DiscardedMR/Weeks
Mandrels	=DiscardedMandrels*MandrelWeight/Weeks
Total	=SUM(D3:D10)
Environmental Categories	Waste/Week
Ext Haz Sub-Rep Quantity	=SUM(Ext Haz Sub Rep Quantity)/Weeks
Ext Haz Sub-TPQ	=SUM(Ext Haz Sub TPQ)/Weeks
Toxic Chemical	=SUM(Toxic Chemical)/Weeks
TRI Chemical	=SUM(TRI Chemical)/Weeks
SARA H-1	=SUM(SARAH1)/Weeks
SARA H-2	=SUM(SARAH2)/Weeks
SARA P-3	=SUM(SARAP3)/Weeks
SARA P-4	=SUM(SARAP4)/Weeks
SARA P-5	=SUM(SARAP5)/Weeks

Environmental Database	Cost/Finished part
Waste Type	Avg
Discarded RM's	=SUM(CostMR*Sheet2!B36,CostMPAdh1*Sheet2!E36,CostMPAdh2*Sheet2!F36,CostLM1*Sheet2!G36,CostLM2*Sheet2!H36,CostMM1*Sheet2!J36,CostMM2*Sheet2!K36,CostResin*Sheet2!L36,CostF1*Sheet2!M36,CostF2*Sheet2!N36,CostA1*Sheet2!O36,CostA2*Sheet2!P36,CostCA*Sheet2!Q36,CostPrepreg*Sheet2!R36,CostSolvMP*Sheet2!S36,CostSolv1*Sheet2!T36,CostSolv2*Sheet2!U36,CostSolvMR*Sheet2!V36,CostAM1*Sheet2!X36,CostAm2*Sheet2!Y36,Sheet2!I36*CostMPPart1,Sheet2!J36*CostMPPart2,Sheet2!AA36*CostBags,Sheet2!AB36*CostAP1,Sheet2!AC36*CostAP2,Sheet2!AD36*CostAP3,Sheet2!AE36*CostAP4)/MAX(Ship)
Total Amount of Mat'l in Scrap	=SUM(CostMR*Sheet2!B38,CostMPAdh1*Sheet2!E38,CostMPAdh2*Sheet2!F38,CostLM1*Sheet2!G38,CostLM2*Sheet2!H38,CostMM1*Sheet2!J38,CostMM2*Sheet2!K38,CostResin*Sheet2!L38,CostF1*Sheet2!M38,CostF2*Sheet2!N38,CostA1*Sheet2!O38,CostA2*Sheet2!P38,CostCA*Sheet2!Q38,CostPrepreg*Sheet2!R38,CostSolvMP*Sheet2!S38,CostSolv1*Sheet2!T38,CostSolv2*Sheet2!U38,CostSolvMR*Sheet2!V38,CostAM1*Sheet2!X38,CostAm2*Sheet2!Y38,Sheet2!C38*CostMPPart1,Sheet2!D38*CostMPPart2,Sheet2!W38*CostBags,Sheet2!Z38*CostAP1,Sheet2!AA38*CostAP2,Sheet2!AB38*CostAP3,Sheet2!AC38*CostAP4)/MAX(Ship)
Machine Waste	=SUM(CostLM1*Sheet2!G46,CostLM2*Sheet2!H46,CostResin*Sheet2!L46,CostF1*Sheet2!M46,CostF2*Sheet2!N46,CostA1*Sheet2!O46,CostA2*Sheet2!P46,CostCA*Sheet2!Q46,CostPrepreg*Sheet2!R46)/MAX(Ship)
Cuttings	=SUM(CostLM1*Sheet2!G47,CostLM2*Sheet2!H47,CostResin*Sheet2!L47,CostF1*Sheet2!M47,CostF2*Sheet2!N47,CostA1*Sheet2!O47,CostA2*Sheet2!P47,CostCA*Sheet2!Q47,CostPrepreg*Sheet2!R47)/MAX(Ship)
Waste Resin	=SUM(CostResin*Sheet2!L48,CostF1*Sheet2!M48,CostF2*Sheet2!N48,CostA1*Sheet2!O48,CostA2*Sheet2!P48,CostCA*Sheet2!Q48,CostPrepreg*Sheet2!R48)/MAX(Ship)
Solvent Bottoms	=SUM(CostResin*Sheet2!L49,CostF1*Sheet2!M49,CostF2*Sheet2!N49,CostA1*Sheet2!O49,CostA2*Sheet2!P49,CostCA*Sheet2!Q49,CostPrepreg*Sheet2!R49,CostSolvMP*Sheet2!S49,CostSolv1*Sheet2!T49,CostSolv2*Sheet2!U49,CostSolvMR*Sheet2!V49)/MAX(Ship)
Air	=SUM(CostSolvMP*Sheet2!S50,CostSolv1*Sheet2!T50,CostSolv2*Sheet2!U50,CostSolvMR*Sheet2!V50)/MAX(Ship)
Discarded Mat'ls used for good parts or WIP	=SUM(F11:F14)
Mandrel Mat'ls	=SUM(CostMM1*Sheet2!J37,CostMM2*Sheet2!K37)/MAX(Ship)
Bag Mat'ls	=(Sheet2!W37*CostBags)/MAX(Ship)
Mold Release	=SUM(CostMR*Sheet2!B37)/MAX(Ship)
Mandrels	=CostMandrel*NewMand/MAX(Ship)
Total	=SUM(F3:F10)
Environmental Categories	Usage/Finished Part
Ext Haz Sub-Rep Quantity	=SUM(UsageExtHazQuantity)/MAX(Ship)
Ext Haz Sub-TPQ	=SUM(UsageExtHazTPQ)/MAX(Ship)
Toxic Chemical	=SUM(UsageToxicChemical)/MAX(Ship)
TRI Chemical	=SUM(UsageTRI)/MAX(Ship)
SARA H-1	=SUM(UsageSH1)/MAX(Ship)
SARA H-2	=SUM(UsageSH2)/MAX(Ship)
SARA P-3	=SUM(UsageSP3)/MAX(Ship)
SARA P-4	=SUM(UsageSP4)/MAX(Ship)
SARA P-5	=SUM(UsageSP5)/MAX(Ship)

Quality Database	Wt/Finished Part
Process Scrap	Avg
Mandrel Prep	=SUM(Sheet2!B39,Sheet2!E39,Sheet2!F39,Sheet2!G39,Sheet2!H39,Sheet2!J39:Sheet2!V39,Sheet2!X39,Sheet2!Y39,Sheet2!C39*MPPart1Weight,Sheet2!D39*MPPart2Weight,Sheet2!W39*BagWeight,Sheet2!Z39*APart1Weight,Sheet2!AA39*APart2Weight,Sheet2!AB39*APart3Weight,Sheet2!AC39*APart4Weight)/MAX(Ship)
Fil Winding	=SUM(Sheet2!B40,Sheet2!E40,Sheet2!F40,Sheet2!G40,Sheet2!H40,Sheet2!J40:Sheet2!V40,Sheet2!X40,Sheet2!Y40,Sheet2!C40*MPPart1Weight,Sheet2!D40*MPPart2Weight,Sheet2!W40*BagWeight,Sheet2!Z40*APart1Weight,Sheet2!AA40*APart2Weight,Sheet2!AB40*APart3Weight,Sheet2!AC40*APart4Weight)/MAX(Ship)
Cure	=SUM(Sheet2!B41,Sheet2!E41,Sheet2!F41,Sheet2!G41,Sheet2!H41,Sheet2!J41:Sheet2!V41,Sheet2!X41,Sheet2!Y41,Sheet2!C41*MPPart1Weight,Sheet2!D41*MPPart2Weight,Sheet2!W41*BagWeight,Sheet2!Z41*APart1Weight,Sheet2!AA41*APart2Weight,Sheet2!AB41*APart3Weight,Sheet2!AC41*APart4Weight)/MAX(Ship)
Mandrel Removal	=SUM(Sheet2!B42,Sheet2!E42,Sheet2!F42,Sheet2!G42,Sheet2!H42,Sheet2!J42:Sheet2!V42,Sheet2!X42,Sheet2!Y42,Sheet2!C42*MPPart1Weight,Sheet2!D42*MPPart2Weight,Sheet2!W42*BagWeight,Sheet2!Z42*APart1Weight,Sheet2!AA42*APart2Weight,Sheet2!AB42*APart3Weight,Sheet2!AC42*APart4Weight)/MAX(Ship)
Finishing	=SUM(Sheet2!B43,Sheet2!E43,Sheet2!F43,Sheet2!G43,Sheet2!H43,Sheet2!J43:Sheet2!V43,Sheet2!X43,Sheet2!Y43,Sheet2!C43*MPPart1Weight,Sheet2!D43*MPPart2Weight,Sheet2!W43*BagWeight,Sheet2!Z43*APart1Weight,Sheet2!AA43*APart2Weight,Sheet2!AB43*APart3Weight,Sheet2!AC43*APart4Weight)/MAX(Ship)
Batch QI	=SUM(Sheet2!B44,Sheet2!E44,Sheet2!F44,Sheet2!G44,Sheet2!H44,Sheet2!J44:Sheet2!V44,Sheet2!X44,Sheet2!Y44,Sheet2!C44*MPPart1Weight,Sheet2!D44*MPPart2Weight,Sheet2!W44*BagWeight,Sheet2!Z44*APart1Weight,Sheet2!AA44*APart2Weight,Sheet2!AB44*APart3Weight,Sheet2!AC44*APart4Weight)/MAX(Ship)
Ind QI	=SUM(Sheet2!B45,Sheet2!E45,Sheet2!F45,Sheet2!G45,Sheet2!H45,Sheet2!J45:Sheet2!V45,Sheet2!X45,Sheet2!Y45,Sheet2!C45*MPPart1Weight,Sheet2!D45*MPPart2Weight,Sheet2!W45*BagWeight,Sheet2!Z45*APart1Weight,Sheet2!AA45*APart2Weight,Sheet2!AB45*APart3Weight,Sheet2!AC45*APart4Weight)/MAX(Ship)
Total	=SUM(B3:B9)
Material Scrap	Avg
Mold Release	=MRScrap/MAX(Ship)
MP Adh Mat'ls	=SUM(MPAdhScrap)/MAX(Ship)
Liner Mat'ls	=SUM(LMatlsScrap)/MAX(Ship)
Mandrel Mat'ls	=SUM(MMatlsScrap)/MAX(Ship)
Resin	=ResinScrap/MAX(Ship)
Fiber	=SUM(FiberScrap)/MAX(Ship)
Additive1	=Add1Scrap/MAX(Ship)
Additive2	=Add2Scrap/MAX(Ship)
Cure Agent	=CAScrap/MAX(Ship)
Prepreg	=PrepregScrap/MAX(Ship)
Solvent-MP	=SolvMPScrap/MAX(Ship)
Solvent-1 FW	=Solv1Scrap/MAX(Ship)
Sovent-2 FW	=Solv2Scrap/MAX(Ship)
Solvent - MR	=SolvMRScrap/MAX(Ship)
Bag Mat'ls	=BagScrap*BagWeight/MAX(Ship)
Assem Mat'l1	=AM1Scrap/MAX(Ship)
Assem Mat'l2	=AM2Scrap/MAX(Ship)
Parts-MP	=(MPPart1Scrap*MPPart1Weight+MPPart2Scrap*MPPart2Weight)/MAX(Ship)
Parts-Assem	=(APart1Scrap*APart1Weight+APart2Scrap*APart2Weight+APart3Scrap*APart3Weight+APart4Scrap*APart4Weight)/MAX(Ship)
Total	=SUM(B14:B32)

Quality Database	Wt/Finished Part
Process Scrap	Avg
Mandrel Prep	=SUM(Sheet2!B39,Sheet2!E39,Sheet2!F39,Sheet2!G39,Sheet2!H39,Sheet2!J39:Sheet2!V39,Sheet2!X39,Sheet2!Y39,Sheet2!C39*MPPart1Weight,Sheet2!D39*MPPart2Weight,Sheet2!W39*BagWeight,Sheet2!Z39*APart1Weight,Sheet2!AA39*APart2Weight,Sheet2!AB39*APart3Weight,Sheet2!AC39*APart4Weight)/MAX(Ship)
Fil Winding	=SUM(Sheet2!B40,Sheet2!E40,Sheet2!F40,Sheet2!G40,Sheet2!H40,Sheet2!J40:Sheet2!V40,Sheet2!X40,Sheet2!Y40,Sheet2!C40*MPPart1Weight,Sheet2!D40*MPPart2Weight,Sheet2!W40*BagWeight,Sheet2!Z40*APart1Weight,Sheet2!AA40*APart2Weight,Sheet2!AB40*APart3Weight,Sheet2!AC40*APart4Weight)/MAX(Ship)
Cure	=SUM(Sheet2!B41,Sheet2!E41,Sheet2!F41,Sheet2!G41,Sheet2!H41,Sheet2!J41:Sheet2!V41,Sheet2!X41,Sheet2!Y41,Sheet2!C41*MPPart1Weight,Sheet2!D41*MPPart2Weight,Sheet2!W41*BagWeight,Sheet2!Z41*APart1Weight,Sheet2!AA41*APart2Weight,Sheet2!AB41*APart3Weight,Sheet2!AC41*APart4Weight)/MAX(Ship)
Mandrel Removal	=SUM(Sheet2!B42,Sheet2!E42,Sheet2!F42,Sheet2!G42,Sheet2!H42,Sheet2!J42:Sheet2!V42,Sheet2!X42,Sheet2!Y42,Sheet2!C42*MPPart1Weight,Sheet2!D42*MPPart2Weight,Sheet2!W42*BagWeight,Sheet2!Z42*APart1Weight,Sheet2!AA42*APart2Weight,Sheet2!AB42*APart3Weight,Sheet2!AC42*APart4Weight)/MAX(Ship)
Finishing	=SUM(Sheet2!B43,Sheet2!E43,Sheet2!F43,Sheet2!G43,Sheet2!H43,Sheet2!J43:Sheet2!V43,Sheet2!X43,Sheet2!Y43,Sheet2!C43*MPPart1Weight,Sheet2!D43*MPPart2Weight,Sheet2!W43*BagWeight,Sheet2!Z43*APart1Weight,Sheet2!AA43*APart2Weight,Sheet2!AB43*APart3Weight,Sheet2!AC43*APart4Weight)/MAX(Ship)
Batch QI	=SUM(Sheet2!B44,Sheet2!E44,Sheet2!F44,Sheet2!G44,Sheet2!H44,Sheet2!J44:Sheet2!V44,Sheet2!X44,Sheet2!Y44,Sheet2!C44*MPPart1Weight,Sheet2!D44*MPPart2Weight,Sheet2!W44*BagWeight,Sheet2!Z44*APart1Weight,Sheet2!AA44*APart2Weight,Sheet2!AB44*APart3Weight,Sheet2!AC44*APart4Weight)/MAX(Ship)
Ind QI	=SUM(Sheet2!B45,Sheet2!E45,Sheet2!F45,Sheet2!G45,Sheet2!H45,Sheet2!J45:Sheet2!V45,Sheet2!X45,Sheet2!Y45,Sheet2!C45*MPPart1Weight,Sheet2!D45*MPPart2Weight,Sheet2!W45*BagWeight,Sheet2!Z45*APart1Weight,Sheet2!AA45*APart2Weight,Sheet2!AB45*APart3Weight,Sheet2!AC45*APart4Weight)/MAX(Ship)
Total	=SUM(B3:B9)
Material Scrap	Avg
Mold Release	=MRScrap/MAX(Ship)
MP Adh Mat'ls	=SUM(MPAdhScrap)/MAX(Ship)
Liner Mat'ls	=SUM(LMatlsScrap)/MAX(Ship)
Mandrel Mat'ls	=SUM(MMatlsScrap)/MAX(Ship)
Resin	=ResinScrap/MAX(Ship)
Fiber	=SUM(FiberScrap)/MAX(Ship)
Additive1	=Add1Scrap/MAX(Ship)
Additive2	=Add2Scrap/MAX(Ship)
Cure Agent	=CAScrap/MAX(Ship)
Prepreg	=PrepregScrap/MAX(Ship)
Solvent-MP	=SolvMPScrap/MAX(Ship)
Solvent-1 FW	=Solv1Scrap/MAX(Ship)
Sovent-2 FW	=Solv2Scrap/MAX(Ship)
Solvent - MR	=SolvMRScrap/MAX(Ship)
Bag Mat'ls	=BagScrap*BagWeight/MAX(Ship)
Assem Mat'l1	=AM1Scrap/MAX(Ship)
Assem Mat'l2	=AM2Scrap/MAX(Ship)
Parts-MP	=(MPPart1Scrap*MPPart1Weight+MPPart2Scrap*MPPart2Weight)/MAX(Ship)
Parts-Assem	=(APart1Scrap*APart1Weight+APart2Scrap*APart2Weight+APart3Scrap*APart3Weight+APart4Scrap*APart4Weight)/MAX(Ship)
Total	=SUM(B14:B32)

Quality Database	Cost/Part
Process Scrap	
Mandrel Prep	=SUM(CostMR*Sheet2!B39,CostMPAdh1*Sheet2!E39,CostMPAdh2*Sheet2!F39,CostLM1*Sheet2!G39,CostLM2*Sheet2!H39,CostMM1*Sheet2!J39,CostMM2*Sheet2!K39,CostResin*Sheet2!L39,CostF1*Sheet2!M39,CostF2*Sheet2!N39,CostA1*Sheet2!O39,CostA2*Sheet2!P39,CostCA*Sheet2!Q39,CostPrepreg*Sheet2!R39,CostSolvMP*Sheet2!S39,CostSolv1*Sheet2!T39,CostSolv2*Sheet2!U39,CostSolvMR*Sheet2!V39,CostAM1*Sheet2!X39,CostAm2*Sheet2!Y39,Sheet2!C39*CostMPPart1,Sheet2!D39*CostMPPart2,Sheet2!W39*CostBags,Sheet2!Z39*CostAP1,Sheet2!AA39*CostAP2,Sheet2!AB39*CostAP3,Sheet2!AC39*CostAP4)/MAX(Ship)
Fil Winding	=SUM(CostMR*Sheet2!B40,CostMPAdh1*Sheet2!E40,CostMPAdh2*Sheet2!F40,CostLM1*Sheet2!G40,CostLM2*Sheet2!H40,CostMM1*Sheet2!J40,CostMM2*Sheet2!K40,CostResin*Sheet2!L40,CostF1*Sheet2!M40,CostF2*Sheet2!N40,CostA1*Sheet2!O40,CostA2*Sheet2!P40,CostCA*Sheet2!Q40,CostPrepreg*Sheet2!R40,CostSolvMP*Sheet2!S40,CostSolv1*Sheet2!T40,CostSolv2*Sheet2!U40,CostSolvMR*Sheet2!V40,CostAM1*Sheet2!X40,CostAm2*Sheet2!Y40,Sheet2!C40*CostMPPart1,Sheet2!D40*CostMPPart2,Sheet2!W40*CostBags,Sheet2!Z40*CostAP1,Sheet2!AA40*CostAP2,Sheet2!AB40*CostAP3,Sheet2!AC40*CostAP4)/MAX(Ship)
Cure	=SUM(CostMR*Sheet2!B41,CostMPAdh1*Sheet2!E41,CostMPAdh2*Sheet2!F41,CostLM1*Sheet2!G41,CostLM2*Sheet2!H41,CostMM1*Sheet2!J41,CostMM2*Sheet2!K41,CostResin*Sheet2!L41,CostF1*Sheet2!M41,CostF2*Sheet2!N41,CostA1*Sheet2!O41,CostA2*Sheet2!P41,CostCA*Sheet2!Q41,CostPrepreg*Sheet2!R41,CostSolvMP*Sheet2!S41,CostSolv1*Sheet2!T41,CostSolv2*Sheet2!U41,CostSolvMR*Sheet2!V41,CostAM1*Sheet2!X41,CostAm2*Sheet2!Y41,Sheet2!C41*CostMPPart1,Sheet2!D41*CostMPPart2,Sheet2!W41*CostBags,Sheet2!Z41*CostAP1,Sheet2!AA41*CostAP2,Sheet2!AB41*CostAP3,Sheet2!AC41*CostAP4)/MAX(Ship)
Mandrel Removal	=SUM(CostMR*Sheet2!B42,CostMPAdh1*Sheet2!E42,CostMPAdh2*Sheet2!F42,CostLM1*Sheet2!G42,CostLM2*Sheet2!H42,CostMM1*Sheet2!J42,CostMM2*Sheet2!K42,CostResin*Sheet2!L42,CostF1*Sheet2!M42,CostF2*Sheet2!N42,CostA1*Sheet2!O42,CostA2*Sheet2!P42,CostCA*Sheet2!Q42,CostPrepreg*Sheet2!R42,CostSolvMP*Sheet2!S42,CostSolv1*Sheet2!T42,CostSolv2*Sheet2!U42,CostSolvMR*Sheet2!V42,CostAM1*Sheet2!X42,CostAm2*Sheet2!Y42,Sheet2!C42*CostMPPart1,Sheet2!D42*CostMPPart2,Sheet2!W42*CostBags,Sheet2!Z42*CostAP1,Sheet2!AA42*CostAP2,Sheet2!AB42*CostAP3,Sheet2!AC42*CostAP4)/MAX(Ship)
Finishing	=SUM(CostMR*Sheet2!B43,CostMPAdh1*Sheet2!E43,CostMPAdh2*Sheet2!F43,CostLM1*Sheet2!G43,CostLM2*Sheet2!H43,CostMM1*Sheet2!J43,CostMM2*Sheet2!K43,CostResin*Sheet2!L43,CostF1*Sheet2!M43,CostF2*Sheet2!N43,CostA1*Sheet2!O43,CostA2*Sheet2!P43,CostCA*Sheet2!Q43,CostPrepreg*Sheet2!R43,CostSolvMP*Sheet2!S43,CostSolv1*Sheet2!T43,CostSolv2*Sheet2!U43,CostSolvMR*Sheet2!V43,CostAM1*Sheet2!X43,CostAm2*Sheet2!Y43,Sheet2!C43*CostMPPart1,Sheet2!D43*CostMPPart2,Sheet2!W43*CostBags,Sheet2!Z43*CostAP1,Sheet2!AA43*CostAP2,Sheet2!AB43*CostAP3,Sheet2!AC43*CostAP4)/MAX(Ship)
Batch QI	=SUM(CostMR*Sheet2!B44,CostMPAdh1*Sheet2!E44,CostMPAdh2*Sheet2!F44,CostLM1*Sheet2!G44,CostLM2*Sheet2!H44,CostMM1*Sheet2!J44,CostMM2*Sheet2!K44,CostResin*Sheet2!L44,CostF1*Sheet2!M44,CostF2*Sheet2!N44,CostA1*Sheet2!O44,CostA2*Sheet2!P44,CostCA*Sheet2!Q44,CostPrepreg*Sheet2!R44,CostSolvMP*Sheet2!S44,CostSolv1*Sheet2!T44,CostSolv2*Sheet2!U44,CostSolvMR*Sheet2!V44,CostAM1*Sheet2!X44,CostAm2*Sheet2!Y44,Sheet2!C44*CostMPPart1,Sheet2!D44*CostMPPart2,Sheet2!W44*CostBags,Sheet2!Z44*CostAP1,Sheet2!AA44*CostAP2,Sheet2!AB44*CostAP3,Sheet2!AC44*CostAP4)/MAX(Ship)
Ind QI	=SUM(CostMR*Sheet2!B45,CostMPAdh1*Sheet2!E45,CostMPAdh2*Sheet2!F45,CostLM1*Sheet2!G45,CostLM2*Sheet2!H45,CostMM1*Sheet2!J45,CostMM2*Sheet2!K45,CostResin*Sheet2!L45,CostF1*Sheet2!M45,CostF2*Sheet2!N45,CostA1*Sheet2!O45,CostA2*Sheet2!P45,CostCA*Sheet2!Q45,CostPrepreg*Sheet2!R45,CostSolvMP*Sheet2!S45,CostSolv1*Sheet2!T45,CostSolv2*Sheet2!U45,CostSolvMR*Sheet2!V45,CostAM1*Sheet2!X45,CostAm2*Sheet2!Y45,Sheet2!C45*CostMPPart1,Sheet2!D45*CostMPPart2,Sheet2!W45*CostBags,Sheet2!Z45*CostAP1,Sheet2!AA45*CostAP2,Sheet2!AB45*CostAP3,Sheet2!AC45*CostAP4)/MAX(Ship)
Total	=SUM(F3:F9)
Material Scrap	Avg
Mold Release	=(MRScrap*CostMR)/MAX(Ship)
MP Adh Mat'ls	=(MPAdhesive1Scrap*CostMPAdh1+MPAdhesive2Scrap*CostMPAdh2)/MAX(Ship)
Liner Mat'ls	=(LM1Scrap*CostLM1+LM2Scrap*CostLM2)/MAX(Ship)
Mandrel Mat'ls	=(MM1Scrap*CostMM1+MM2Scrap*CostMM2)/MAX(Ship)
Resin	=(ResinScrap*CostResin)/MAX(Ship)
Fiber	=(F1Scrap*CostF1+F2Scrap*CostF2)/MAX(Ship)
Additive1	=(Add1Scrap*CostA1)/MAX(Ship)

Additive2	=(Add2Scrap*CostA2)/MAX(Ship)
Cure Agent	=(CAScrap*CostCA)/MAX(Ship)
Prepreg	=(PrepregScrap*CostPrepreg)/MAX(Ship)
Solvent-MP	=(SolvMPScrap*CostSolvMP)/MAX(Ship)
Solvent-1 FW	=(Solv1Scrap*CostSolv1)/MAX(Ship)
Sovent-2 FW	=(Solv2Scrap*CostSolv2)/MAX(Ship)
Solvent - MR	=(SolvMRScrap*CostSolvMR)/MAX(Ship)
Bag Mat'ls	=(BagScrap*CostBags)/MAX(Ship)
Assem Mat'l1	=(AM1Scrap*CostAM1)/MAX(Ship)
Assem Mat'l2	=(AM2Scrap*CostAm2)/MAX(Ship)
Parts-MP	=(MPPart1Scrap*CostMPPart1+MPPart2Scrap*CostMPPart2)/MAX(Ship)
Parts-Assem	=(APart1Scrap*CostAP1+APart2Scrap*CostAP2+APart3Scrap*CostAP3+APart4Scrap*CostAP4)/MAX(Ship)
Total	=SUM(F14:F32)

Cost Database	Cost	Direct Costs/Part	Direct Costs/Week
Energy($/Kw)	=NRGCost	=PartNRG*B2	=B2*TotalNRG
Materials($/lb or part)			
Mold Release	=CostMR	=PartMR*B4	=WeekMR*B4
MP Part1	=CostMPPart1	=PartMPPart1*B5	=WeekMPPart1*B5
MP Part2	=CostMPPart2	=PartMPPart2*B6	=WeekMPPart2*B6
MPAdhesive1	=CostMPAdh1	=PartMPAdh1*B7	=WeekMPAdh2*B7
MPAdhesive2	=CostMPAdh2	=PartMPAdh2*B8	=WeekMPAdh1*B8
Liner Mat'l1	=CostLM1	=PartLM1*B9	=WeekLM1*B9
Liner Mat'l2	=CostLM2	=PartLM2*B10	=WeekLM2*B10
Mandrel	=CostMandrel	=PartMandrel*B11	=WeekMandrel*B11
Mand Mat'l1	=CostMM1	=PartMM1*B12	=WeekMM1*B12
Mand Mat'l2	=CostMM2	=PartMM2*B13	=WeekMM2*B13
Resin	=CostResin	=PartResin*B14	=WeekResin*B14
Fiber1	=CostF1	=PartF1*B15	=WeekF1*B15
Fiber2	=CostF2	=PartF2*B16	=WeekF2*B16
Additive1	=CostA1	=PartA1*B17	=WeekA1*B17
Additive2	=CostA2	=PartA2*B18	=WeekA2*B18
Cure Agent	=CostCA	=PartCA*B19	=WeekCA*B19
Prepreg	=CostPrepreg	=PartPrepreg*B20	=WeekPrepreg*B20
Solvent-MP	=CostSolvMP	=PartSolvMP*B21	=WeekSolvMP*B21
Solvent1	=CostSolv1	=PartSolv1*B22	=WeekSolv1*B22
Solvent2	=CostSolv2	=PartSolv2*B23	=WeekSolv2*B23
Solvent MR	=CostSolvMR	=PartSolvMR*B24	=WeekSolvMR*B24
Bag Mat'ls	=CostBags	=PartBags*B25	=WeekBags*B25
Assem Mat'l1	=CostAM1	=PartAM1*B26	=WeekAM1*B26
Assem Mat'l2	=CostAm2	=PartAM2*B27	=WeekAM2*B27
APart1	=CostAP1	=PartAP1*B28	=WeekAP1*B28
APart2	=CostAP2	=PartAP2*B29	=WeekAP2*B29
APart3	=CostAP3	=PartAP3*B30	=WeekAP3*B30
APart4	=CostAP4	=PartAP4*B31	=WeekAP4*B31
Labor ($/hour)			
General	1	=GenLabor*B33*time/MAX(Ship)	=GenLabor*B33*time/Weeks
Maintenance	1	=MaintLabor*B34*time/MAX(Ship)	=MaintLabor*B34*time/Weeks
Waste Disposal($/lb)			
Hazardous	10		
Nonhazardous	1		
Total Direct Costs		=SUM(C2:C37)	=SUM(E2:E37)

Energy Database	Usage KW	KWhr/part	Avg KWhr/week
Mandrel Prep	10	=(MPcycle)/100*time*B2/MAX(Ship)	=(MPcycle)/100*time*B2/Weeks
Filament Winding	10	=FW1cycle/100*time*B3/MAX(Ship)	=(FW1cycle)/100*time*B3/Weeks
Cure1	10	=(MoveC1)/100*time*B4/MAX(Ship)	=(MoveC1)/100*time*B4/Weeks
Cure3	10	=CycleC3/100*time*B5/MAX(Ship)	=(CycleC3)/100*time*B5/Weeks
Cure4	10	=CycleC4/100*time*B6/MAX(Ship)	=(CycleC4)/100*time*B6/Weeks
Mandrel Removal	10	=MR1cycle/100*time*B7/MAX(Ship)	=(MR1cycle)/100*time*B7/Weeks
Machining	10	=Mach1cycle/100*time*B8/MAX(Ship)	=(Mach1cycle)/100*time*B8/Weeks
Cutting	10	=Cut1cycle/100*time*B9/MAX(Ship)	=(Cut1cycle)/100*time*B9/Weeks
Assembly	10	=As1cycle/100*time*B10/MAX(Ship)	=(As1cycle)/100*time*B10/Weeks
Individual Inspection	10	=QIIcycle/100*time*B11/MAX(Ship)	=(QIIcycle)/100*time*B11/Weeks
Batch Inspection	10	=QIBcycle/100*time*B12/MAX(Ship)	=(QIBcycle)/100*time*B12/Weeks
Total		=SUM(C2:C12)	=SUM(D2:D12)

APPENDIX E

WITNESS Library Files for Individual Submodels for Filament Winding Application

Submodels

The initial DTAME simulation environment is focused on modeling and analysis of filament winding operations. The environment consists of the 12 basic submodels reviewed below.

Manprep1

This submodel models the mandrel preparation operation. It contains three basic elements, the new mandrel buffer (MandBuff), the recycled mandrel buffer (MandRec), two FIFO queues, and the mandrel preparation machine (MandPrep1), a batch machine with a default batch size of 1. The default machine has no setup, does not experience breakdowns, and uses general labor. New and reused mandrels enter the MandBuff while mandrels recycled during this operation are stored in MandRec. MandPrep1 can pull a mandrel from either buffer to begin the mandrel preparation (preference goes to MandRec).

The following actions are initiated upon completion of the mandrel preparation operation:

IF Uses = 0 AND Quality = 0
ManUses = NEGEXP (200,57)
ENDIF
[If mandrel quality is good and Uses (the number of times the mandrel has been used) is equal to zero Assign a new value of ManUses(the number of times the mandrel can be used). This is used to assign a value of Manuses to original mandrels.]
IF Uses > ManUses AND Quality = 0
NewMand = NewMand + 1
Uses = 0
ManUses = NEGEXP (200,57)
ENDIF
[If Uses (the number of times that the mandrel has been used) is greater than ManUses (the number of times the mandrel can be used) and mandrel quality is good then increment NewMand (counter for new mandrels that have been used in process), reset Uses to zero, and assign valaue of ManUses to new mandrel.]
IF Quality = 0
Uses = Uses + 1
ENDIF
[If mandrel quality is good then increment Uses (counter which tracks the number of times that the mandrel has been used)]
Quality = QualMP1 (1)
[Mandrel quality is assigned based on a random sample from the QualMP(1) distribution]
Mandprep = Mandprep + 1
[Increment Mandprep (counter which indicates the number of mandrel preparation operations that have taken place on the part)]
IF Quality = 1
ScrapMP = ScrapMP + 1
ENDIF
[If mandrel quality is poor (1) then increment ScrapMP (mandrel prep scrap counter)]
IF Quality = 1 AND Liner = 1
CHANGE Mandrel to PrepMand
ENDIF
[If mandrel quality is poor (1) and a liner was used (1) then change the part name from Mandrel to PrepMand to reflect completion of the mandrel prep stage]

The completed parts are routed to the next operation as follows:

```
IF Quality = 0
 PUSH to FW1Buff
        [If the mandrel is good then send it to the filament-winding buffer]
ELSEIF Quality = 1 AND Liner = 1
 PUSH to MRBuff
        [If the mandrel is to be scrapped and uses a liner then it is sent to the Mandrel removal
        buffer]
ELSEIF Quality = 1 AND Liner = 0
 PUSH to MandBuff
        [If the mandrel is to be scrapped and doesn't use a liner then the mandrel is sent to the  mandrel
        buffer]
ELSEIF Quality = 2 AND Liner = 1
 PUSH to MandRec
        [If the mandrel can be recycled and it uses a liner then it is sent to the Mandrel
        recycling buffer]
ELSEIF Quality = 2 AND Liner = 0
 PUSH to MandRec
        [If the mandrel can be recycled and it doesn't use a liner then it is sent to the mandrel
        recycling buffer]
ELSE
 Wait
        [Initiate no action until prompted by another operation]
ENDIF
```

Filwind1

This submodels simulates the filament winding operation. It contains two basic elements, the filament winding buffer (FW1Buff) a FIFO queue with a maximum capacity of 1000 parts and the filament winder (FilWind1). The filament winder is modeled as a batch machine with a minimum batch size of 1. The default assumption is that the filament winder has no setup and no default cycle time.

Breakdowns are allocated for cleaning the machine. Breakdowns occur every 7.5 hrs. and their duration follows an Erlang (0.5,3,15) distribution. The cleaning action requires the use of four miscellaneous variables:

Solv1use - Total amount of solvent 1 used during the simulation during normal cleaning of Filament Winding,
Solv1add - Amount of solvent to add to variable Solv1use during normal cleaning operation of Filament Winding,
Solv2use - Total amount of solvent 2 used during simulation during heavy duty cleaning of Filament Winding,
Solv2add - Amount of solvent to add to variable Solv2use during heavy duty cleaning operation of Filament Winding.

The user has the option of choosing general labor or no labor for the filament winder. There are three basic "parts" associated with this submodel: 1) the mandrel (Mandrel), 2) the prepared mandrel (PrepMand), and 3) the filament wound part (FWPart). There are no actions taken upon startup of the filament-winding machine.

The following actions are initiated upon completion of the filament winding operation:

Quality = QualFW1 (4)
[Part quality is assigned based on a random sample from QualFW1 (Filament winding quality distribtuion)]
FW = FW + 1
[Increment FW (counter indicating the nubmer of filament winding operations performed on part)]
CHANGE PrepMand to FWPart
[Change part name from PrepMand to FWPart to indicate completion of the filament winding operation]
IF Quality = 1
ScrapFW = ScrapFW + 1
[If part quality is bad then increment ScrapFW (Filament winding scrap counter)]
ENDIF

After completion of processing parts are routed as follows:

!IF Quality = 0
! PUSH to Cure1 at Rear
!! PUSH to Cure2
!! PUSH to C3Buff
!! PUSH to C4Buff
[If part is good then send part to either Cure 1, Cure 2, Cure 3 buffer, or Cure 4 buffer]
!ELSEIF Quality = 1
! PUSH to MRBuff
[If part is bad then send to the mandrel removal buffer]
!ELSE
! Wait

```
!ENDIF
Wait
```

Cure1

This submodel models an initial curing operation. It contains one element - Cure1 a conveyer. It is a fixed conveyor. The conveyor waits until parts are pushed onto it from a feeding operation. There are no actions initiated when a part joins the conveyor.

The following actions are initiated at the front of the conveyor (Cure1):

CHANGE ALL to CurePart
    [Change part name to CurePart to indicate completion of curing operation]
Cure = Cure + 1
    [Increment Cure (part attributer which indicates the number of curing operations performed on this part)]
Quality = QualC1 (5)
    [Set output quality for this part for this operation by randomly sampling from the QualC1 distribution (Quality distribution for Cure1)]
IF Quality = 1
 ScrapC1 = ScrapC1 + 1
    [If the part must be scrapped increment ScrapC1(Scrap counter for Cure1)]
IF MandRem = 0
  ScrapC = ScrapC + 1
    [If the mandrel has not been removed then increment ScrapC (counter which tracks scrap material) - insures that the mandrel is included in the scrap count]]
ENDIF
ENDIF

After completion of the cure cycle the part is routed as follows:

!IF MandRem = 0
! IF Quality = 0
! PUSH to MRBuff
    [If mandrel has not been removed and the part is good then send to the mandrel removal buffer]
!! PUSH to Cure2
    [If the part is good then send to Cure 2]
!! PUSH to C3Buff
    [If the part is good then send to the Cure 3 buffer]
!! PUSH to C4Buff
    [If the part is good then send to the Cure 4 buffer]
!! PUSH to MachBuff
    [If the part is good then send to Machining buffer]
! ELSEIF Quality = 1
! PUSH to MRBuff
! ENDIF
    [IF the part must be scrapped then send to the mandrel removal buffer]
!ELSEIF MandRem = 1
! IF Quality = 0
!! PUSH to Cure2
!! PUSH to C3Buff
!! PUSH to C4Buff
! PUSH to MachBuff
!! Push to CutBuff
!! Push to AsBuff
!! Push to QIBuff

!! Push to QBBuff
!! Push to Ship

[If the mandrel has been removed and the part is good then send on to one of the other processing stations: Cure 2, Cure 3 buffer, Cure 4 buffer, machine buffer, cut buffer, assembly buffer, quality inspection buffer, quality batch buffer, or Ship]

! ELSEIF Quality = 1
! PUSH to SCRAP
! ENDIF

[If the part must be scraped send to scrap]

!ELSE
! Wait

[Initiate no action until prompted by another operation]

Cure2

This submodels models a room temperature cure operation. It contains two elements - Cure2, a buffer and Cure2M, a dummy machine which contains all the actions. Cure2 is a FIFO buffer with a capacity of 1000 parts.

The following actions are initiated upon completion of Cure2:

```
  Quality = QualC2 (6)
        [Part quality is assigned by a random sample from the QualC2 distribution (Cure 2 quality
        distribution)]
   Cure = Cure + 1
        [Increment Cure(part attribute which indicates the number of curing operations performed on
        this part]
   CHANGE ALL to CurePart
        [Change name to CurePart to indicate completion of curing operation]
   IF Quality = 1
    ScrapC2 = ScrapC2 + 1
        [If part must be scrapped increment ScrapC2 (scrap counter for C2)]
    IF MandRem = 0
     ScrapC = ScrapC + 1
        [If the mandrel has not been removed then increment ScrapC(counter which tracks scrap
        material) -insures that the mandrel is included in the scrap count]
ENDIF
   ENDIF
```

After completion of the cure cycle the part is routed as follows:

```
!IF MandRem = 0
! IF Quality = 0
!  PUSH to MRBuff
        [If mandrel has not been removed and the part is good then send to the mandrel removal buffer]
!! PUSH to Cure1 at Rear
        [If the part is good then send to Cure 1]
!! PUSH to C3Buff
        [If the part is good then send to the Cure 3 buffer]
!! PUSH to C4Buff
        [If the part is good then send to the Cure 4 buffer]
!! PUSH to MachBuff
        [If the part is good then send to Machining buffer]
! ELSEIF Quality = 1
!  PUSH to MRBuff
! ENDIF
        [IF the part must be scrapped then send  to the mandrel removal buffer]
!ELSEIF MandRem = 1
! IF Quality = 0
!! PUSH to Cure1
!! PUSH to C3Buff
!! PUSH to C4Buff
!  PUSH to MachBuff
!!  Push to CutBuff
!!  Push to AsBuff
!!  Push to QIBuff
```

!! Push to QBBuff
!! Push to Ship
[If the mandrel has been removed and the part is good then send on to one of the other processing stations: Cure 1, Cure 3 buffer, Cure 4 buffer, machine buffer, cut buffer, assembly buffer, quality inspection buffer, quality batch buffer, or Ship]
! ELSEIF Quality = 1
! PUSH to SCRAP
! ENDIF
[If the part must be scraped send to scrap]
!ELSE
! Wait
[Initiate no action until prompted by another operation]

Cure3

This submodels models a batch curing operation in an oven or autoclave. It contains two elements - C3Buff a FIFO buffer with a capacity of 1000 parts, and Cure3 a batch machine with a minimum batch size of 1. Cure3 has not setup or breakdowns. Parts are pulled from the cure 3 buffer (C3Buff). The operation uses either no labor or general labor. No actions are initiated upon starting the operation.

The following actions are initiated upon completion of Cure3:

Quality = QualC3 (7)
{Part quality is assigned by a random sample from the QualC3 distribution (Cure 3 quality distribution)]
Cure = Cure + 1
[Increment Cure (counter which indicates the number of curing operations performed on this part]
CHANGE ALL to CurePart
[Change part name to CurePart to indicate completion of curing operation]
IF Quality = 1
ScrapC3 = ScrapC3 + 1
[If part must be scrapped increment ScrapC3 (scrap counter for Cure 3)]
IF MandRem = 1
ScrapC = ScrapC + 1
[If the mandrel has not been removed then increment ScrapC(counter which tracks scrap material) -insures that the mandrel is included in the scrap count]
ENDIF

After completion of the cure cycle the part is routed as follows:

!IF MandRem = 0
! IF Quality = 0
! PUSH to MRBuff
[If mandrel has not been removed and the part is good then send to the mandrel removal buffer]
!! PUSH to Cure1
[If the part is good then send to Cure 1]
!! PUSH to C2
[If the part is good then send to the Cure 2]
!! PUSH to C4Buff
[If the part is good then send to the Cure 4 buffer]
!! PUSH to MachBuff
[If the part is good then send to Machining buffer]
! ELSEIF Quality = 1
! PUSH to MRBuff
! ENDIF
[IF the part must be scrapped send to the mandrel removal buffer]
!ELSEIF MandRem = 1
! IF Quality = 0
!! PUSH to Cure1
!! PUSH to Cure2
!! PUSH to C4Buff
! PUSH to MachBuff
!! Push to CutBuff
!! Push to AsBuff

!! Push to QIBuff
!! Push to QBBuff
!! Push to Ship

[If the mandrel has been removed and the part is good then send on to one of the other processing stations: Cure 1, Cure 2, Cure 4 buffer, machine buffer, cut buffer, assembly buffer, quality inspection buffer, quality batch buffer, or Ship]

! ELSEIF Quality = 1
! PUSH to SCRAP
! ENDIF

[If the part must be scraped send to scrap]

!ELSE
! Wait

[Initiate no action until prompted by another operation]

Cure4

This submodel models a cure operation in an autoclave which utilizes reusable vacuum bag materials. It consists of three element - 1) C4Buff a FIFO buffer with a maximum capacity of 1000 parts, 2) BagRec a FIFO buffer with a capacity of 1000 parts used for the reusable bags, and 3) a general machine which pulls one bag from BagRec for every part from C4Buff.

The following input rules are used during Cure4:

SEQUENCE /Wait C4Buff#(1),
BagRec#(1)
[Waits for a part to arrive at the Cure4 Buffer (C4Buff) and a recycled bag at BagRec. Must have one of each to begin operation.]

The following actions are initiated upon completion for Cure4:

```
IF TYPE = Bags
 UsesB = UsesB + 1
        [Increment UsesB ( bag use counter)]
 IF UsesB > BagUses
  UsesB = 0
  NewBags = NewBags + 1
        [If UsesB (bag use counter) is greater than BagUses (The number of times the bag can be
reused) then increment NewBags (counter tracking the number of new vacuum bags used)]
  BagUses=Uniform(85,87,9)
        [Assigns new value of BagUses(The number of times the bag can be reused) to new bags]
 ENDIF
ELSE
 Quality = QualC4 (8)
        [Assign part quality level based on a random sample from the QualC4 distribution]
 Cure = Cure + 1
        [Increment Cure (counter tracking the number of cure operations performed on the part).]

 CHANGE ALL to CurePart
        [Rename CurePart to indicate completion of the curing process.]
 IF Quality = 1
  ScrapC4 = ScrapC4 + 1
        [If the part must be scrapped increment ScrapC4 (The Cure4 scrap counter)]
  IF MandRem = 1
   ScrapC = ScrapC + 1
        [If the mandrel has not be removed then increment ScrapC (The mandrel scrap counter)]
  ENDIF
 ENDIF
```

After completion of the cure cycle the part is routed as follows:

```
!IF TYPE = CurePart
!IF MandRem = 0
! IF Quality = 0
!  PUSH to MRBuff
        [If mandrel has not been removed and the part is good then send to the mandrel removal buffer]
!! PUSH to Cure1
```

```
        [If the part is good then send to Cure 1]
!! PUSH to Cure2
        [If the part is good then send to the Cure 2]
!! PUSH to C3Buff
        [If the part is good then send to the Cure 3 buffer]
!! PUSH to MachBuff
        [If the part is good then send to Machining buffer]
! ELSEIF Quality = 1
!  PUSH to MRBuff
        [If the part must be scrapped then send the part to the MRBuff (Mandrel removal buffer)]
!  ENDIF
! ELSEIF MandRem = 1
!  IF Quality = 0
!!  PUSH to Cure1
!!  PUSH to Cure2
!!  PUSH to C3Buff
!   PUSH to MachBuff
!!  PUSH to CutBuff
!!  PUSH to AsBuff
!!  PUSH to QBBuff
!!  PUSH to QIBBuff
!!  PUSH to Ship
        [If the mandrel has been removed and the part is good then send it to one of the following
        locations: Cure1, Cure2, C3Buff (Cure3 buffer), MachBuff (Machining buffer), CutBuff
(Cutting         buffer), AsBuff (Assembly buffer), QBBuff (quality batch inspection buffer), QIBuff
(Quality         inspection buffer), or Ship]
!  ELSEIF Quality = 1
!   PUSH to SCRAP
        [If the part must be scrapped then send it to SCRAP]
!  ENDIF
! ENDIF
!ELSEIF TYPE = Bags
        [If this is a bag then send it to BagRec (the recycled bag buffer)]
! PUSH to BagRec
!ELSE
! Wait
```

Manrem1

This submodels models the mandrel removal process. It consists of two elements: 1) the mandrel removal buffer MRBuff a FIFO buffer with a maximum capacity of 1000 parts; and 2) the mandrel removal operation ManRem1. ManRem1 is modeled as a general machine with a capacity of 1 part. Parts are pulled from MRBuff when a part is available and when the processing station is free. The default object does not require setup and does not experience breakdowns. The machine uses either no labor or general labor based on user preferences.

The following actions are initiated upon startup of the mandrel removal operation:

MRUses = Uses
MRManUse = ManUses
[MRUses and MRManUse are given the value of Uses(the number of times the mandrel has been uses) and ManUses (the number of times the mandrel can be used) to reassign these values to mandrels upon completion of mandrel removal operation]

The following actions are initiated upon completion of the mandrel removal operation:

MandRem = MandRem + 1
[Increment MandRem (attribute indicating whether mandrel has been removed)]
IF TYPE = Mandrel
CHANGE Mandrel to Mandrel
[If the part attribute is mandrel then change it's name to Mandrel. This allows the else statement below to function properly.]
MandRem = 0
[Set Mandrem to 0 (attribute indicating that mandrel has not been removed)]
Uses = MRUses
ManUses = MRManUse
[Reset Uses (the number of times the mandrel has been reused) to MRUses and ManUses (the number of times the mandrel can be used) to MRManUse for all mandrels]
Quality = 0
[Set quality level to 0 (good)]
ELSE
CHANGE ALL to MRPart
[Rename part MRPart to signify completion of the mandrel removal operation]
ENDIF
IF TYPE = MRPart
IF Quality = 0
Quality = QualMR (9)
[If this is a MRPart and the quality level is 0 (good) then assign the quality level via a random sample from the QualMR (mandrel removal quality) distribution. Quality is not assigned to returning mandrels.]
ELSEIF Quality = 1
Quality = 1
[If a poor quality part from a previous operation has been sent to Mandrel Removal keep the quality (1) the same.]
ENDIF
ENDIF

After completion of Mandrel Removal the part is routed as follows:

```
!IF TYPE = MRPart
! IF Quality = 0
!  PUSH MRPart to MachBuff
!! PUSH MRPart to AsBuff
!! PUSH MRPart to CutBuff
!! PUSH MRPart to Cure1 at Rear
!! PUSH MRPart to Cure2
!! PUSH MRPart to C3Buff
!! PUSH MRPart to C4Buff
!! PUSH MRPart to QIBuff
!!  PUSH MRPart to QBBuff
!! PUSH MRPart to SHIP
```

[If this is a MRPart (Mandrel removal part) and the quality is good then send the part to MachBuff (Machining buffer) or any of the other locations listed]

```
! ELSEIF Quality = 1
!  PUSH MRPart to SCRAP
```

[If this is a MRPart (Mandrel removal part) and the quality is bad then send the part to SCRAP]

```
! ENDIF
!ELSEIF TYPE = Mandrel
! PUSH Mandrel to MandBuff
```

[If this is Mandrel then send it to MandBuff (Mandrel preparation buffer)]

```
!ELSE
! Wait
```

Mach1

This submodels models a machining operation. It consists of two basic modeling elements: MachBuff a FIFO buffer with a capacity of 1000 parts, and Mach1 a single machine. The default submodel has no setup, does not experience breakdowns. Parts are pulled from MachBuff as they become available and upon completion of processing of any parts in Mach1. No actions are initiated upon startup of Mach1.

The following actions are initiated upon completion of processing on Mach1:

Quality = QualMach (10)
    [Assign part quality by a random sample from QualMach (Machining quality distribution)]
IF Assem = 0 AND Cut = 0
 Machine = 1
    [If the part has not been assembled or cut the set Machine attribute to 1 (indicates that machining is the first finishing operation)]
ELSEIF Assem > 0 AND Cut > 0
 Machine = 3
    [If the part has been assembled and cut then set Machine attribute to 3 (indicates that machining is the third finishing operation)]
ELSE
 Machine = 2
    [Set Machining attribute to 2 (indicates that machining is the second finishing operation)]
ENDIF
CHANGE ALL to MachPart
    [Change part name to MachPart to indicate completion of the machining operation]
IF Quality = 1
 ScrapMa = ScrapMa + 1
    [If part quality is bad then increment ScrapMa (Machining scrap counter)]
 IF MandRem = 1
  ScrapF = ScrapF + 1
    [If the mandrel has been removed then increment ScrapF]
 ENDIF
 IF Assem > 0 AND Assem > Cut
  ScrapF1 = ScrapF1 + 1
    [If the part was assembled but not cut then increment ScrapF1 (counter which indicates that scrap includes assembly materials and parts - calculations utilize full amount of assembled parts)]
ELSEIF Assem > 0 AND Assem < Cut
  ScrapF0 = ScrapF0 + 1
    [If the part was assembled and cut then increment ScrapF0 (counter which indicates that scrap includes assembly material and parts - calculations utilize full amount of assembled parts divided by the number of cut parts)]
 ENDIF
 IF Machine > 0 AND Cut = 0
  ScrapF2 = ScrapF2 + 1
    [If the part was machined but not cut then increment ScrapF2 (counter, which indicates that the amount of composite and liner materials to be scrapped equals original amount minus the percent of material discarded during machining operation).]
 ELSEIF Cut > 0 AND Machine = 0
  ScrapF3 = ScrapF3 + 1

[If the part was cut but not machined the increment ScrapF3 (counter which indicates that amount of composite and liner materials to be scrapped equals the original amount minus the percent of materials discarded during the cutting operation divided by the number of cut parts).]

ELSEIF Cut > 0 AND Machine > 0
ScrapF4 = ScrapF4 + 1

[If the part has been machined and cut the increment ScrapF4 (counter indicating that amount of composite and liner material to be scrapped is equal to the original amount minus the percent discarded during both the cutting and machining operations divided by the number of cut parts.]

ELSEIF Cut = 0 AND Machine = 0
ScrapF5 = ScrapF5 + 1

[If the part has not been cut or machined increment ScrapF4 (counter indicating that scrap equals the original amount of composite and liner materials)]

ENDIF
ENDIF

After completion of processing parts are routed as follows:

!IF Quality = 0
! PUSH to CutBuff
!! PUSH to AsBuff
!! PUSH to QIBuff
!! PUSH to QBBuff
!! PUSH to MRBuff
!! PUSH to Ship

[If the part is good then send it to one of the following locations:, CutBuff (Cutting buffer), AsBuff (Assembly buffer), QBBuff (Quality Batch Inspection buffer), QIBuff (Quality Inspection buffer), MRBuff (Mandrel Removal buffer), or Ship]

!ELSEIF Quality = 1
! IF MandRem = 1
! PUSH to SCRAP
! ELSEIF MandRem = 0
! PUSH to MRBuff

[If the part is bad and the mandrel has been removed send to Scrap. If the part is bad and the mandrel has not been removed send it to the Mandrel Removal buffer.]

! ENDIF
!ELSE
! Wait

Assem1

This submodel models an assembly operation. It consists of two basic modeling elements: AsBuff a FIFO buffer with a capacity of 1000 parts. And Assem1 a single machine. The default submodel has no setup, does not experience breakdowns. Parts are pulled from AsBuff as they become available and upon completion of the processing of any parts in Assem1. No actions are initiated upon startup of Assem1.

The following actions are initiated upon completion of processing on Assem1:

Quality = QualA (11)
    [Assign part quality based on a random sample from the Assembly quality distribution QualA]
IF Cut = 0 AND Machine = 0
 Assem = 1
    [If the part has not been cut or machined then set Assem attribute to 1 (indicates that assembly is the first finishing operation]
ELSEIF Cut > 0 AND Machine > 0
 Assem = 3
    [If the part has been cut and machined then set Assem attribute to 3 (indicates that assembly is the third finishing operation]
ELSE
 Assem = 2
    [Set Assem attribute to 2 (indicates that assembly is the second finishing operation]
ENDIF
CHANGE ALL to AsPart
    [Change the part name to AsPart to indicate that the part has completed the assembly process]
IF Quality = 1
 ScrapA = ScrapA + 1
    [If part quality is bad increment ScrapA (Assembly scrap counter)]
 IF MandRem = 1
  ScrapF = ScrapF + 1
    [If the mandrel has been removed then increment ScrapF]
 ENDIF
IF Assem > 0 AND Assem > Cut
  ScrapF1 = ScrapF1 + 1
    [If the part was assembled but not cut then increment ScrapF1 (counter which indicates that scrap includes assembly materials and parts - calculations utilize full amount of assembled parts)]
ELSEIF Assem > 0 AND Assem < Cut
  ScrapF0 = ScrapF0 + 1
    [If the part was assembled and cut then increment ScrapF0 (counter which indicates that scrap includes assembly material and parts - calculations utilize full amount of assembled parts divided by the number of cut parts)]
 ENDIF
 IF Machine > 0 AND Cut = 0
  ScrapF2 = ScrapF2 + 1
    [If the part was machined but not cut then increment ScrapF2 (counter, which indicates that the amount of composite and liner materials to be scrapped equals original amount minus the percent of material discarded during machining operation).]
 ELSEIF Cut > 0 AND Machine = 0
  ScrapF3 = ScrapF3 + 1

[If the part was cut but not machined the increment ScrapF3 (counter which indicates that amount of composite and liner materials to be scrapped equals the original amount minus the percent of materials discarded during the cutting operation divided by the number of cut parts).]

```
 ELSEIF Cut > 0 AND Machine > 0
  ScrapF4 = ScrapF4 + 1
```

[If the part has been machined and cut the increment ScrapF4 (counter indicating that amount of composite and liner material to be scrapped is equal to the original amount minus the percent discarded during both the cutting and machining operations divided by the number of cut parts.]

```
 ELSEIF Cut = 0 AND Machine = 0
  ScrapF5 = ScrapF5 + 1
```

[If the part has not been cut or machined increment ScrapF4 (counter indicating that scrap equals the original amount of composite and liner materials)]

```
 ENDIF
ENDIF
```

After completion of processing parts are routed as follows:

```
!IF Quality = 0
!! PUSH to CutBuff
!! PUSH to MachBuff
! PUSH to QIBuff
!! PUSH to QBBuff
!! PUSH to Ship
```

[If the part is good then send it to one of the following locations:, CutBuff (Cutting buffer), MachBuff (Machining buffer), QBBuff (quality batch inspection buffer), QIBuff (Quality inspection buffer), or Ship]

```
!ELSEIF Quality = 1
! PUSH to SCRAP
```

If the part is bad then send to SCRAP

```
!ELSE
! Wait
```

Cut1

This submodel models an cutting operation. It consists of two basic modeling elements: CutBuff a FIFO buffer with a capacity of 1000 parts and Cut1 a production machine which processes one original part at a time. The default submodel has no setup and does not experience breakdowns. Parts are pulled from CutBuff as they become available and upon completion of the processing of any parts in Cut1.

The following actions are initiated upon startup of Cut1.

[The following code transfers the incoming part attributes to process variables which will later be transferred to all cut parts leaving Cut1 so that they retain their incoming attributes.]

CutMP = Mandprep
CutFW = FW
CutCure = Cure
CutMR = MandRem
CutMach = Machine
CutAssem = Assem

The following actions are initiated upon completion of processing on Cut1:

CHANGE ALL to CutPart
    [Rename parts CutPart to indication completion of the cutting operation]
Quality = QualC (12)
    [Assign part quality based on a random sample from the cutting quality distribution QualC (Cut quality distribution)]
Mandprep = CutMP
    [Set the number of mandrel prep operations equal to CutMP for all cut parts]
FW = CutFW
    [Set the number of filament winding operations equal to CutFW for all cut parts]
Cure = CutCure
    [Set the number of cure operations equal to CutCure for all cut parts]
MandRem = CutMR
    [Set the number of mandrel removal operations equal to CutMR for all cut parts]
Machine = CutMach
    [Set the number of machining operations equal to CutMach for all cut parts]
Assem = CutAssem
    [Set the number of assembly operations equal to CutAssem for all cut parts]
IF Assem = 0 AND Machine = 0
 Cut = 1
    [If the part has not been assembled or machined then set Cut equal to 1 (indicates that cutting is the first finishing operation)]
ELSEIF Assem > 0 AND Machine > 0
 Cut = 3
    [If the part has been assembled and machined then set Cut equal to 3 (indicates that cutting is the third finishing operation)]
ELSE
 Cut = 2
    [Set cut equal to 2 to signify that cutting is the second finishing operation]
ENDIF
IF Quality = 1
 ScrapCut = ScrapCut + 1
    [If part quality is bad increment ScrapCut (Cut scrap counter)]

```
IF MandRem = 1
 ScrapF = ScrapF + 1
        [If mandrel has not been removed increment ScrapF (mandrel scrap counter)]
ENDIF
IF Assem > 0 AND Assem > Cut
 ScrapF1 = ScrapF1 + 1
        [If the part was assembled but not cut then increment ScrapF1 (counter which indicates that
        scrap includes assembly materials and parts - calculations utilize full amount of assembled
        parts)]
ELSEIF Assem > 0 AND Assem < Cut
 ScrapF0 = ScrapF0 + 1
        [If the part was assembled and cut then increment ScrapF0  (counter which indicates that scrap
        includes assembly material and parts - calculations utilize full amount of assembled parts divided
        by the number of cut parts)]
ENDIF
IF Machine > 0 AND Cut = 0
 ScrapF2 = ScrapF2 + 1
        [If the part was machined but not cut then increment ScrapF2 (counter, which indicates that
        the amount of composite and liner materials to be scrapped equals original amount minus the
        percent of material discarded during machining operation).]
ELSEIF Cut > 0 AND Machine = 0
 ScrapF3 = ScrapF3 + 1
        [If the part was cut but not machined the increment ScrapF3 (counter which indicates that
        amount of composite and liner materials to be scrapped equals the original amount minus the
        percent of materials discarded during the cutting operation divided by the number of cut parts).]
ELSEIF Cut > 0 AND Machine > 0
 ScrapF4 = ScrapF4 + 1
        [If the part has been machined and cut the increment ScrapF4 (counter indicating that amount of
        composite and liner material to be scrapped is equal to the original amount minus the percent
        discarded during both the cutting and machining operations divided by the number of cut parts.]
ELSEIF Cut = 0 AND Machine = 0
 ScrapF5 = ScrapF5 + 1
        [If the part has not been cut or machined increment ScrapF4 (counter indicating that scrap equals
        the original amount of composite and liner materials)]
ENDIF
ENDIF
```

After completion of processing parts are routed as follows:

```
!IF Quality = 0
!! PUSH to MachBuff
! PUSH to AsBuff
!! PUSH to QIBuff
!! PUSH to QBBuff
!! PUSH to Ship
        [If the part is good then send it to one of the following locations:, MachBuff (Machining
buffer), AsBuff  (Assembly buffer), QIBuff (Quality inspection buffer), QBBuff (quality batch inspection
buffer), or Ship]
!ELSEIF Quality = 1
! PUSH to SCRAP
        [If the part is bad then send to SCRAP]
!ELSE
! Wait
!ENDIF
Wait
```

QIbatch

This submodel models an batch inspection operation. It consists of two basic modeling elements: QBBuff a FIFO buffer with a capacity of 1000 parts. And QIBatch a general machine. The default submodel has no setup, does not experience breakdowns, and uses General labor. Parts are pulled from QBBuff as they become available and upon completion of the processing of any parts in QIBatch.

The following actions are initiated upon startup of Q1Batch.

QBatch = QualQIB (13)
    [Batch quality is assigned based on a random sample from QualQIB (batch quality distribution)]

The following actions are initiated upon completion of processing on Q1Batch:

IF QBatch = 1
 ScrapQB = ScrapQB + 1
    [If batch quality is unacceptable (1) then increment ScrapQB (Batch quality inspection scrap counter)]
ENDIF
Quality = Qbatch
    [Set part quality attribute to Qbatch value]
CHANGE ALL to InspPart
    [Rename parts InspPart to indicate completion of the Batch quality inspection]
QIB = QIB + 1
    [Increment Q1B (attribute indicating the number of batch quality inspections

After completion of processing parts are routed as follows:

!IF Quality = 0
!! PUSH to Ship
! PUSH to QIBuff
    [If part quality is good then send the part to SHIP or to the QIBuff (Quality inspection buffer)]
!ELSEIF Quality = 1
! PUSH to SCRAP
    [If the part is bad then send to SCRAP]
!ELSE
! Wait
!ENDIF
Wait

QIInd

This submodel models a single inspection operation. It consists of two basic modeling elements: As a FIFO buffer with a capacity of 1000 parts. And QIInd a single machine. The default submodel has no setup, does not experience breakdowns, and uses General labor. Parts are pulled from QIBuff as they become available and upon completion of the processing of any parts in QIInd. No actions are initiated upon startup of QIInd.

The following actions are initiated upon completion of processing on QIInd:

CHANGE ALL to InspPart
    Change the part name to InspPart to indicate completion of the Inspection Operation
Quality = QualQII (14)
    Assign part quality via a random sample from the QII quality distribution
QII = QII + 1
    [Increment QII (counter indicating the number of individual quality inspections that have taken place on the part)]
ShipQII = NSHIP (InspPart)
    [Increment ShipQII (counter tracking the number of parts shipped from Qiind)]
IF Quality = 1
 ScrapQI = ScrapQI + 1
    [If part quality is unacceptable increment ScrapQI (Individual quality inspection scrap counter)]
ENDIF

After completion of processing parts are routed as follows:

IF Quality = 0
PUSH to SHIP
! PUSH to QBBuff
    [If part quality is good then send the part to SHIP or to the QIBuff (Quality inspection buffer)]
ELSEIF Quality = 1
 PUSH to SCRAP
    [If the part is bad then send to SCRAP]
ELSE
 Wait
ENDIF

APPENDIX F

Report Definitions for Filament Winding Application

Report Definitions

Amount or # used for original part - Amount or number used of a certain material in the processing of each part during the original processing of that part.

% Discarded as RM - Percent of material discarded in raw material state. Percentage is based on "total material purchased" not "total used for processing".

% Waste Resin - Percent of material which ends up as cured resin waste. Percentage is based on "total resin mixture made" not "total used for processing".

% Machine Waste & % Cutting Waste - Percent of material lost (does not end up in finished product) during machining or cutting process. Percentage is based on weight of part before any finishing, including machining or cutting, is done.

% Solvent Waste - For composites, it is the percentage of the "total resin mixture made" not "used" which ends up as waste in the solvent recycling process. For solvents, it is the percentage of solvents used (including recycled solvents) which end up as waste in the solvent recycling process.

Amount Needed/finished part - Total amount of material coming out of process divided by the number of good parts. Ignores work in process.

Average (lb. or #) needed/ week - Total amount of material coming in to system/ weeks. Includes work in process.

Amount in finished part - Theoretical amount of each material which should be in each finished part based on machine waste, cutting waste, number of parts that original part is cut into and type of material or part.

Amount in - Total amount of material coming into system includes material used for processing, and allows for discarded raw materials and materials in cured waste resin and solvent bottoms. For solvents, "amount in" includes only new solvent coming into the system (i.e. it excludes the recycle stream). The table below shows how the amount of materials used in the various processing steps is calculated.

Material Calculation Table

Processing Step	Number used to calculate	Comments
Mandrel Preparation	# of mandrels leaving MandBuff * Amount of materials used for original part	No materials are used for recycled mandrels so could not use Mandrel Prep cycles. Could have small error if Mand Prep batch size is greater than 1.
Filament Winding	FW Batch Size * FW cycles * Amount of materials used for original part	

Material Calculation Table (cont.)

Processing Step	Number used to calculate	Comments
Cure3	Cure3 Batch Size * BuffC3 * Number of Bags used for curing operation	Bag is put on before operation begins so use buffer input.
Mandrel Removal	ManRem cycles * Amount of materials used for original part	Single machine only. No need for batch size.
Assembly	Assemble cycles * Amount of materials used for original part	Single machine only. No need for batch size.

Discarded Materials used for Good Parts - Amount of materials, which would not end up in finished part, that are used in making good parts. This would be included for mold release, mandrel materials and solvents.

Discarded Scrap or Materials used for Scrap Parts - Materials in or used for parts which are of poor quality. This section is divided into the major processing categories. The scrap materials for the batch quality inspection process also includes any materials/parts thrown away during destructive testing. This information was not calculated for both solvents used for cleaning the filament winder, reusable mandrels or arbors, and reusable bags.

Solvent bottoms - Amount of composite materials and solvents which end up in the unrecyclable mixture during solvent recycling. See "% Solvent Waste".

Air - Used only for solvents at present. It is the amount of solvents which end up in the air and unrecyclable.

% Scrap - Percentage of material used in the production of poor quality product. It is calculated by dividing "Discarded Scrap or Materials used for Scrap Parts" by "Amount In" for each material.

% Waste - Percentage of material which has been discarded as waste (includes % Scrap).

% WIP - Percentage of material which is currently in process.

% Good - Percentage of materials which has been used in the production of good quality product.

Total - %Waste + % WIP + % Good.

APPENDIX G

Material Balance Information for Filament Winding Application

Material Balance Information

Type of Material: Mold Release
Units of Measure: Weight
Report Column: B
Material Balance Equations:

Amount In = MandPrep Usage + Discarded RM;s
See Rows 34 and 36

Amount Out = Discarded RM's + Discarded Mat'ls Used for Good Parts or WIP + Scrap(MP)+ Scrap(FW) + Scrap(Cure) + Scrap(ManRem) + Scrap(Finishing) + Scrap(Other)
= MRCycles*Amount used +Discarded RM's
See Rows 35, 36, 37, 39-43, and 46

Type of Material: MP Part
Examples: Up to two different parts which can be attached to composite part during Mandrel Preparation
Units of Measure: Number of Parts
Report Columns: C,D
Material Balance Equations:

Amount In = MandPrep Usage + Discarded RM's
See Rows 34 and 36

Amount Out = Discarded RM's + Scrap(MP) + Scrap(FW) + Scrap(Cure) + Scrap(ManRem) + Scrap(Finishing) + Scrap(BatchQI) +Scrap(Ind QI) + Good Parts
See Rows 35, 36, 39-45, 52

Type of Material: Liner Materials
Examples: Up to two materials used for a liner in the composite part
Units of Measure: Weight
Report Columns: E,F
Material Balance Equations:

Amount In = MandPrep Usage + Discarded RM's
See Rows 34 and 36

Amount Out = Discarded RM's + Scrap(MP) + Scrap(FW) + Scrap(Cure) + Scrap(ManRem) + Scrap(Finishing) + Scrap(BatchQI) +Scrap(Ind QI) + Machine Waste + Cutting Waste + Good Parts
See Rows 35, 36, 39-45, 47, 48, and 52

Type of Material: Mandrel
Units of Measure: Number of Mandrels
Report Column: G
Material Balance Equations:

Amount In = Original Mandrels + New Mandrels
See Rows 27 and 34

Amount Out = New Mandrels
See Row 35

Type of Materials: Mandrel Materials
Example: Up to two types of materials used for one use mandrels(plaster, sand, etc.)
Units of Measure: Weight
Report Columns: H,I
Material Balance Equations:

Amount In = MandPrep Usage + Discarded RM's
See Rows 34 and 36

Amount Out = Discarded RM's + Discarded Mat'ls Used for Good Parts or WIP + Scrap(MP)+ Scrap(FW) + Scrap(Cure) + Scrap(ManRem) + Scrap(Finishing) + Scrap(Other)
= MRCycles*Amount used +Discarded RM's
See Rows 35, 36, 37, 39-43, and 46

Type of Material: Composite
Examples: Resin, Fiber, Additives, Curing Agent, Prepreg
Units of Measure: Weight
Report Columns: J-P
Material Balance Equations:

Amount In = FW Usage + Discarded RM's + Waste Resin + Solvent Bottoms
See Rows 34, 36, 49 and 50

Amount Out = Discarded RM's + Scrap(FW) + Scrap (Cure) +Scrap(ManRem) +Scrap(Finishing) + Scrap(BatchQI) + Scrap(IndQI) + Cutting Waste + Machine Waste + Waste Resin + Solvent Bottoms + Good Parts
See Rows 35, 36, 40-45, 47, 48, 49, 50

Type of Material: Solvents
Examples: Solvents from Mandrel Prep, Filament Winding, Mandrel Removal
Units of Measure: Weight
Report Columns: Q-T
Material Balance Equations:

Amount In = Usage * (1-%Recycled)
See Row 34

Amount Out = Solvent Bottoms + Air
See Rows 50 and 51

Type of Materials: Bag Materials
Examples: Recyclable or one use bags used in autoclave
Units of Measure: Number of Bags
Report Columns: U
Material Balance Equations;

Recyclable
Amount In = Original Bags + New Bags
See Rows 27 and 34

Amount Out = New Bags
See Row 35

One Use
Amount In = Cure3 Usage + Discarded RM's
See Rows 34 and 36

Amount Out = Finished Bags + Discarded RM's
See Rows 35 and 36

Type of Material: Assembly Materials
Examples: Up to two types of materials used for assembly
Units of Measure: Weight
Report Columns: V,W
Material Balance Equations:

Amount In = Asseml Usage + Discarded RM's
See Rows 34 and 36

Amount Out = Discarded RM's + Scrap(Finishing) + Scrap(BatchQI) + Scrap(IndQI) +Good Parts
See Rows 35, 36, 43-45, and 52

Type of Material: Assembly Parts
Examples: Up to four different parts which be attached to composite part during assembly operation
Units of Measure: Number of Parts
Report Columns: X-AA
Material Balance Equations:

Amount In = Assem1 Usage + Discarded RM's
See Rows 34 and 36

Amount Out = Discarded RM's + Scrap(Finishing) + Scrap(BatchQI) + Scrap(IndQI) + Good Parts
See Rows 35, 36, 43-45, and 52

APPENDIX H

Question Sets and Reports for Filament Winding Validation Example

Mandrel Preparation
Question Set 2-1

Option 2

Materials

Mold Release: Yes — If yes: Name: Teflon ___
Cost: .05/gram
Amount used per mandrel: 2 g
% discarded as unused mold release: 0%

Liner Mat'ls: Yes — If yes: How many materials used? 1
Name: Shrink Tubing
Cost: .10/g
Amount used per mandrel: 45 g
% discarded as unused raw material: 0%

Parts: Yes — If yes: How many different parts used: 1
Name : Aluminum Pole Pieces
Cost: 25.00/ea
Number used per assembly: 2
Weight: 85g
% discarded as unused parts: 0%

Assembly Mat'l: Yes — If yes: How many materials used 2
Name: Kelpoxy G-293
Cost: $1.00/g
Amount used per mandrel: .58 g
% discarded as unused raw material: 0%
Name: Versamid-140
Cost: $2.50/g
Amount used per mandrel: 4.5 g
% discarded as unused raw material: 0%

Cleaner(for cleaning): Yes — If yes: Name: Acetone
Cost: .01/g
Amount used per mandrel: 114g
Recycled Yes (X) No____
% Recycled: 70%
% Released to Air: 20%
% Solid/liquid waste: 10%

Mandrels

Number Available:30
Cost: $1000.00
Weight 4536 g
How many uses before discarding? 1000
Do scrap parts during mandrel preparation need to go to mandrel removal station for disassembly? Yes

Labor

Is labor required? No — If yes: How many workers needed?

Breakdowns

Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)

If yes: How many different types? 1-10

For each type: Frequency? time between breakdowns

Labor? (maintenance assumed) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Set up Procedures

Any set up procedures? Yes

If yes: Frequency of setup? 1

Labor? Type: General Amount: 1

Length of time? Triangle (4,5,6, 72) hrs

Cycle Time

Cycle time? 5 hrs

Energy Usage

Energy Usage? Yes If yes: Rate? 10 KW

Configuration

# of Machines? 1

Batch Size? 10

Quality

% Scrap? 2%

% Recycle? 0%

% Good Parts equals: 98%

Mandrel Preparation
Question Set 2-2

Option 1

Materials:

Mandrel Mat'ls: Yes

If yes: How many materials used: 2
Name: Sand
Cost: .0035/g
Amount used per mandrel: 1342.8 g
% discarded as unused raw material: 2%
Name: Sodium Silicate
Cost: .0035/g
Amount used per mandrel: 107.6 g
% discarded as unused raw material: 2%

Mold Release: No

Liner Mat'ls: Yes

If yes: How many materials used? 1
Name: Shrink Tubing
Cost: .10/g
Amount used per mandrel: 45 g
% discarded as unused raw material: 0%

Parts: Yes

If yes: How many different parts used: 1
Name : Aluminum Pole Pieces
Cost: 25.00/ea
Number used per assembly: 2
Weight: 85g
% discarded as unused parts: 0%

Assembly Mat'l: Yes

If yes: How many materials used 2
Name: Kelpoxy G-293
Cost: $1.00/g
Amount used per mandrel: .58 g
% discarded as unused raw material: 0%
Name: Versamid-140
Cost: $2.50/g
Amount used per mandrel: 4.5 g
% discarded as unused raw material: 0%

Cleaner(for cleaning): No

Mandrel Arbor

Number Available: 30
Cost: $500.00
Weight 2268 g
How many uses before discarding? 1000
Do scrap parts during mandrel preparation need to go to mandrel removal station for disassembly? No

Labor

Is labor required? No — If yes: How many workers needed?

Breakdowns

Any breakdowns or work stoppages? Yes___ No (X)

If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Set up Procedures

Any set up procedures? Yes
If yes: Frequency of setup? 1
Labor? Type: General Amount: 1
Length of time? Triangle (4,5,6, 72) hrs

Cycle Time

Cycle time? 5 hrs

Energy Usage

Energy Usage? Yes If yes: Rate? 10 KW

Configuration

# of Machines? 1
Batch Size? 10

Quality

% Scrap? 5%
% Recycle? 0%
% Good Parts equals: 95%

Filament Winding
Question Set 3-1

Materials

Resin: Yes — If yes: Name: Epon 826
Cost: .01/g
MSDS: H-1
Amount in Fil Wound Part: 50 g
% discarded as uncured resin: 0%
% discarded as cured resin waste: 5%
% discarded in solvent waste: 15%

Fiber-1:Yes — If yes: Name: Graphite Fiber
Cost: .05/g
Amount in Fil Wound Part: 100 g
% discarded as unused fiber: 0%

Fiber-2: No

Additive-1: Yes — If yes: Name: Viscosity Improver RD-2
Cost: .50/g
Amount in Fil Wound Part: 5 g
% discarded as unused additive: 0%

Additive-2: Yes — If yes: Name: Hardener 906
Cost: .25/g
MSDS: H-1, H-2, TRI
Amount in Fil Wound Part: 45 g
% discarded as unused additive 0%

Curing Agent: Yes — If yes: Name: EMI-24
Cost: $2.00/g
MSDS: H-1,H-2
Amount in Fil Wound Part: .75 g
% discarded as unused curing agent: 0%

or

Prepreg : No

Labor

Is labor required? Yes (X) No____ If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters _________

Scheduled Maintenance (other than cleaning)

Any scheduled maintenance? Yes (X) No___
If yes: How many different types? (1)-10
For each type: Frequency? 167 hrs
Labor? (maintenance assumed) Amount (1)
Length of time? 1
Default - Carriage system cleaning

Cleaning (Default Values for wet winding only. Default to no cleaning for prepreg.)
Any normal(Resin not set up)? Yes_(X)_ No___
Type of solvent used: Acetone
Cost: .01/g
Amount of solvent used? Normal (510,38, 56) oz.
Recycle Yes _(X)_ No___
% Recycled 0 - 100% (70%)
% Vapor 0-(100-%Recycled)% (20%)
% Solid/liquid Waste (100-[% Recycled + % Vapor])(10%)
Frequency of cleaning? _time between cleanings (7.5 hrs)_
Time required for cleaning? Erlang (.5,3,15)
Labor? Type (general assumed) How many? _(1)_
Any non-normal(Resin set up)? Yes_•_ No _(X)_
Type of solvent used: _(Acetone)/list/insert MSDS info/cost_
Amount of solvent used? _(0)_
Recycle Yes _(X)_ No___
% Recycled 0 - 100% (70%)
% Vapor 0-(100-%Recycled)% (20%)
% Solid/liquid Waste (100-[% Recycled + % Vapor])(10%)
Frequency of cleaning? _time between cleanings (7.5 hrs)_
Time required for cleaning? Type _(deterministic)/triangular/probabilistic_ Parameters _.5 hrs._
Labor? Type (general assumed) How many? _(1)_

Set up Procedures
Any set up procedures? Yes_(X)_ No___
If yes: Frequency of setup? _# of cycles between setups(1)_
Labor? Type: General Amount:_(1)_
Length of time? Triangle(.17,.25,.33,78)

Cycle Time (get from manufacturer of machine)
Cycle time? Triangle(.33,.42,.5,83)

Energy Usage
Energy Usage? Yes If yes: Rate? 10 KW

Configuration
# of Machines? 1
# of Spindles/machine 1
Buffer Capacity: 20

Quality
% Scrap? 5%
% Good Parts equals 95%

Cure
Question Set 4-4
(Module 4-3)

Labor
Is labor required? Yes___No(X) If yes: How many workers needed?
Breakdowns
Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________
Scheduled Maintenance
Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________
Set up Procedures
Any set up procedures? Yes
If yes: Frequency of setup? 1
Labor? Type General Amount: 1
Length of time? .5 hrs
Cycle Time
Cure time? 24 hrs
Energy Usage
Energy Usage? Yes If yes: Rate? 10 KW
Configuration
# of Ovens? 1
Capacity of each oven? 10
Buffer Capacity ? 0
Quality
% Scrap? 0%
% Good Parts equals 100%

Mandrel Removal
Question Set 5-2
(Module 5-1)

Option 1

Materials

Solvent: Yes

If yes: Name: Water
Amount used per part: 16000 g
Recycled: No
% Recycled 0-100%
% Released to Air 0-(100-%Recycled)
% Solid/liquid waste (100-[%Recycled + %Vapor])

Labor

Is labor required? Yes (X) No____ If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes___No (X)
If yes: Frequency? time between breakdowns
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)
If yes: How many different types? 1-10
For each type: Frequency? time between breakdowns
Labor? (maintenance assumed) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Set up Procedures

Any set up procedures? Yes___ No (X)
If yes: Frequency of setup? # of cycles between setups
Labor? Type general/(maintenance) Amount (1)
Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Cycle Time

Cycle time? Triangle (

Energy Usage

Energy Usage? Yes___No (X) If yes: Rate? Kw

Configuration

# of Machines? (1)-20
Buffer Capacity?_____

Quality

% Scrap? (0)-100%
% Good Parts equals [100-% Scrap]

Mandrel Removal
Question Set 5-1
(Module 5-1)

Option 2

Labor

Is labor required? Yes (X) No____ If yes: How many workers needed? (1)

Breakdowns

Any breakdowns or work stoppages? Yes___ No (X)

If yes: Frequency? time between breakdowns

Labor? Type general/(maintenance) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Scheduled Maintenance

Any scheduled maintenance? Yes___ No (X)

If yes: How many different types? 1-10

For each type: Frequency? time between breakdowns

Labor? (maintenance assumed) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Set up Procedures

Any set up procedures? Yes___ No (X)

If yes: Frequency of setup? # of cycles between setups

Labor? Type general/(maintenance) Amount (1)

Length of time? Type (deterministic)/triangular/probabilistic Parameters ________

Cycle Time

Cycle time? Type (deterministic)/triangular/probabilistic Parameters ________

Energy Usage

Energy Usage? Yes___ No (X) If yes: Rate? Kw

Configuration

# of Machines? (1)-20

Buffer Capacity?_____

Quality

% Scrap? (0)-100%

% Good Parts equals [100-% Scrap]

APPENDIX I

Genetic Algorithm Report

Genetic Algorithms for Improving Manufacturing Operations

Charles L. Karr and Eric Wilson
Aerospace Engineering and Mechanics Department
Box 870280
The University of Alabama
Tuscaloosa, AL 35487-0280

1.0 Introduction

Environmental impact must be assessed during the design phase of product development. Assessing pollution impacts, recycling issues, and energy consumption during the early phases of product development will result in long term savings and a reduction in pollution and waste products. Tools are needed which allow designers to understand the consequences of their decisions regarding manufacturing options.

Tools for simulating manufacturing systems have greatly enhanced in the last decade. However, these tools have not directly addressed the issues of simulation definition in the context of environmental concerns and multiple metrics for performance. Nor do simulation tools provide cost modeling or optimization routines. The typical simulation tool concentrates on providing throughput and capacity information for assessing the impact of product mix changes, or information on an individual station's speed and reliability as it relates to overall system performance.

In order to address the lack of such tools, the Design Tool for Assessing Manufacturing Environmental Impact (DTAME) will build on capabilities and systems developed in previous research projects: a system used to critique the applicability of a particular composite manufacturing process and an interactive simulator developed to rapidly define, model, and evaluate electronic manufacturing systems. Results from the Army's fuzzy logic controller for helicopter flight control will also be utilized as part of a search strategy involving genetic algorithms to optimize system configuration. DTAME will aid in making environmentally conscious decisions, and apply appropriate metrics and regulations within the normal context of simulation development and use to generate critiques of proposed actions. Although the targeted domain is polymer based composite materials, the architecture of the proposed system is generic so as to allow for "plug and play" modularity.

The DTAME project will focus on the identification of parameters necessary to characterize the environmental and energy impact of key production processes. The output of such a simulation model will provide engineers and managers with information on system output, queue length, and production lead times, as well as energy usage and the types and quantities of scrap and hazardous material produced.

Research will also address the development of capabilities to not only determine the absolute performance of the system (i.e., kilowatt hours of energy used per year, tons of hazardous material produced, etc.), but is will also allow users to say with a high degree of certainty which of two alternative systems is environmentally preferable.

To this end, the objective of the current study was to investigate the use of genetic algorithms (GAs) in improving the manufacturing system configuration. This report describes a preliminary effort in which the simulation environment WITNESS was used in conjunction with a GA to optimize the cycle times of two simulated manufacturing lines. Results are promising, and further areas of investigation are suggested.

2.0 GA Performance on a Small Assembly Line Optimization Problem

The first portion of this research effort was focused on a small assembly line system. As shown in Diagram 1, this simple system consisted of a single line containing three consecutive machines and an inspection site. A single part (referred to as a "widget") was entered into the system at the first machine (Machine 1), worked on, and then passed by conveyor (Conveyor 1) to the second machine (Machine 2). At Machine 2, the widget was worked on again, and then sent by a long conveyor (Conveyor 2) to Machine 3. After being worked on once again at Machine 3 (using labor from Operator), a final conveyor (Conveyor 3) sent the part to the inspection site (Inspection). From there, the part was shipped.

Diagram 2.1 shows the flow of parts from one machine to another, and Tables 2.1-2.5 show the settings for each segment of this assembly line.

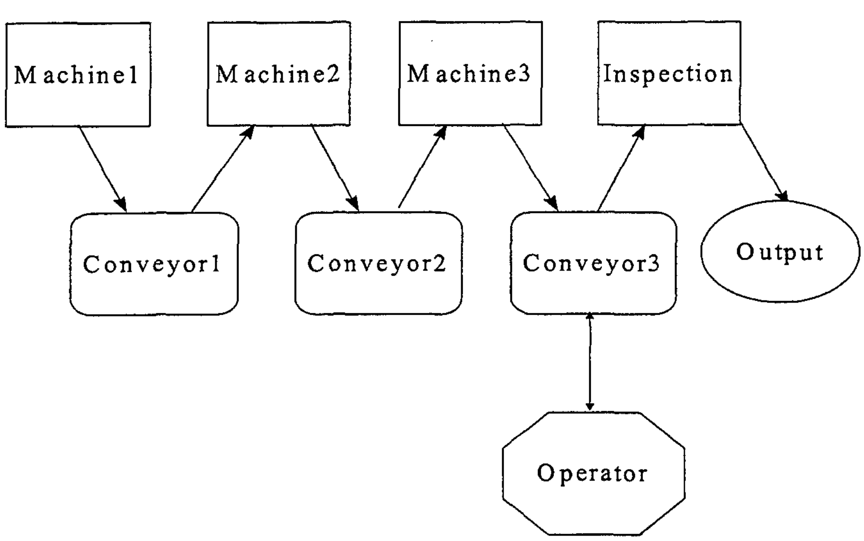


Diagram 2.1: Assembly Line - Small Problem

Table 2.1: Machine Data

	Machine 1	**Machine 2**	**Machine 3**	**Inspection**
Quantity	1	1	1	1
Priority	Lowest	Lowest	Lowest	Lowest
Cycle Time	**Variable**	**Variable**	**Variable**	**Variable**
Type	Single	Single	Single	Single
Input	PULL from Widget out of WORLD	Wait	PULL from Conveyor 2	PULL from Conveyor 3
Output	PUSH to Conveyor 1 at rear	PUSH to Conveyor 2 at rear	PUSH to Inspection	PUSH to SHIP
Reporting	Individual	Individual	Individual	Individual
Shift	N/A	N/A	N/A	N/A
Setup:	N/A	N/A		N/A
Mode			No. of Operations	
Interval:				
# of Operations			5	
Ops To First Setup			No. of Operations	
Setup Time			12.0	
Labor Rule			Operator	
Breakdowns:	N/A	N/A		N/A
Check Only at Start of Cycle?			Yes	
Mode			Busy Time	
Time Between Failures			NEGEXP (60,1)	
Repair Time			LOGNORML (10,2,2)	
Labor Rule			Operator	
Actions on Finish				Output=Output+1

Table 2.2: Conveyor Data

	Conveyor 1	Conveyor 2	Conveyor 3
Quantity	1	2	1
Priority	Lowest	Lowest	Lowest
Type	Queuing	Queuing	Queuing
Length	10	10	10
Maximum Capacity	10	10	10
From	Wait	Wait	Wait
To	PUSH to Machine2	Wait	Wait
Index Time	0.5	0.5	0.5

Table 2.3: Labor Data

	Operator
Shifts	Always available
Quantity	1.0
Allowance	0.0
Reporting	On

Table 2.4: Variable Data

	Output
Quantity	1
Reporting	On
Type	Integer

Table 2.5: Part Data

	Widget
Group Number	1
Reporting	On

The blank spaces in the tables above are data areas in WITNESS that were not used by those parts/machines/conveyors. Any data areas in WITNESS that are not listed in these tables are either empty of data or not used.

Many of these parameters could potentially be adjusted by the GA. They include Quantity, Priority, Cycle Time, Length, Maximum Capacity, Index Time, and all of the characteristics under Setup and Breakdowns (except Labor Rule). However, the only parameters adjusted by the GA were the Cycle Times of the Machines and the Inspection. In summary, the GA's task was to solve a four parameter optimization problem.

In order to run WITNESS simulations and collect data from them, the GA was placed within Visual Basic as a "front end" program. This program started up WITNESS and opened the simulation module to be tested. The GA then sent WITNESS the necessary data (all of the cycle times of the machines and inspection) and initiated a 500 minute simulation in WITNESS in batch mode. After the simulation was finished, the GA called AFLOW, a WITNESS function that calculated the average time parts spent on the assembly line from start to finish. The objective of the GA in this research was to minimize AFLOW.

Before running the GA, each machine was provided with minimum and maximum cycle times (all in minutes). These are shown in Table 2.6.

Table 2.6: Cycle Time Ranges - Small Problem

	Minimum	**Maximum**
Machine 1	1	8
Machine 2	2	7
Machine 3	3	9
Inspection	0.5	5.2

These parameters served as boundaries for the actual cycle times sent to WITNESS by the GA.

Once the GA sent WITNESS cycle times for the machines, it ran a simulation and collected the necessary data. It then repeated this process. Twenty simulations (one for each member of the GA population) were run. Once this generation was completed, the highest and lowest times calculated from AFLOW were written to a file, along with the generation number, average time, total time, and cycle times of the machines that had the lowest AFLOW value. Once this was done, a new generation of twenty members was formed, and the simulations were run again.

For the purposes of this research, three different methods of determining the lowest value of AFLOW were used. The first was the GA. The second was an "intuitive" method, by which all of the cycle times for all of the machines and inspector were set to their minimum values. Since all of the cycle times were set to their lowest

respective values, a low value of AFLOW was "implied" by this method. The third method was a random selection. 400 sets of cycle times (the same total used by the GA) were randomly generated and tested. Their best and average performances were calculated. Below are two charts portraying this performance. The first chart shows the average performance of the GA and the random selection along with the "intuitive" result. The second chart shows only the minimum performance of the GA and the random search (since the intuitive answer proved to be drastically higher than the minimum random and GA answers).

Chart 2.1: Average Performance

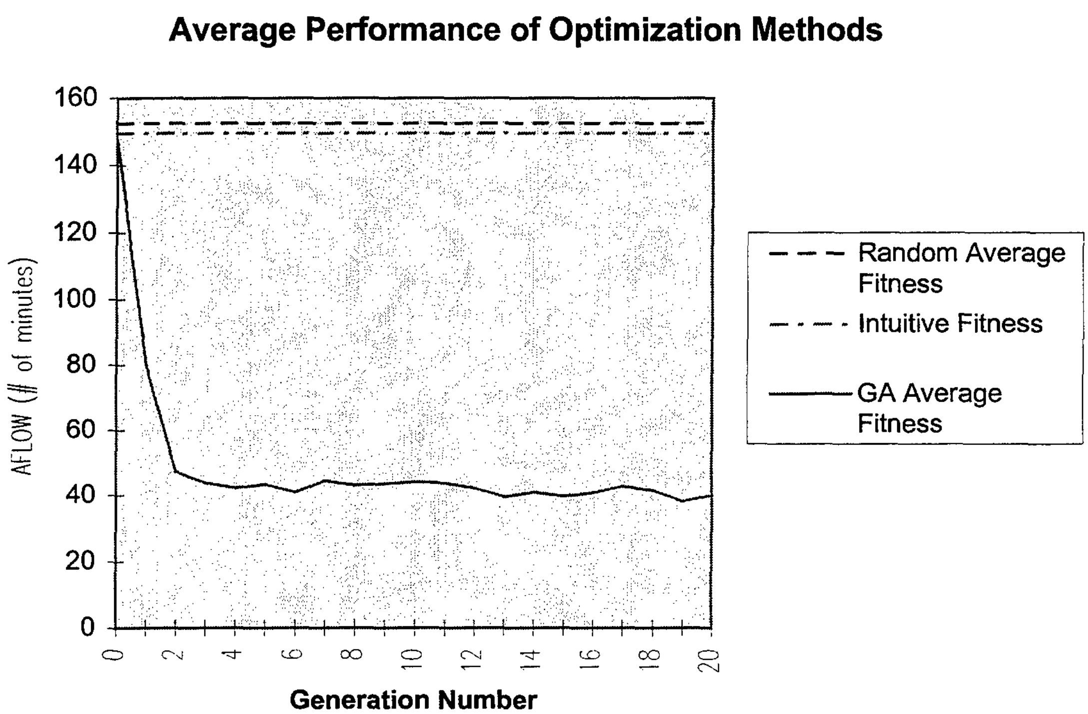
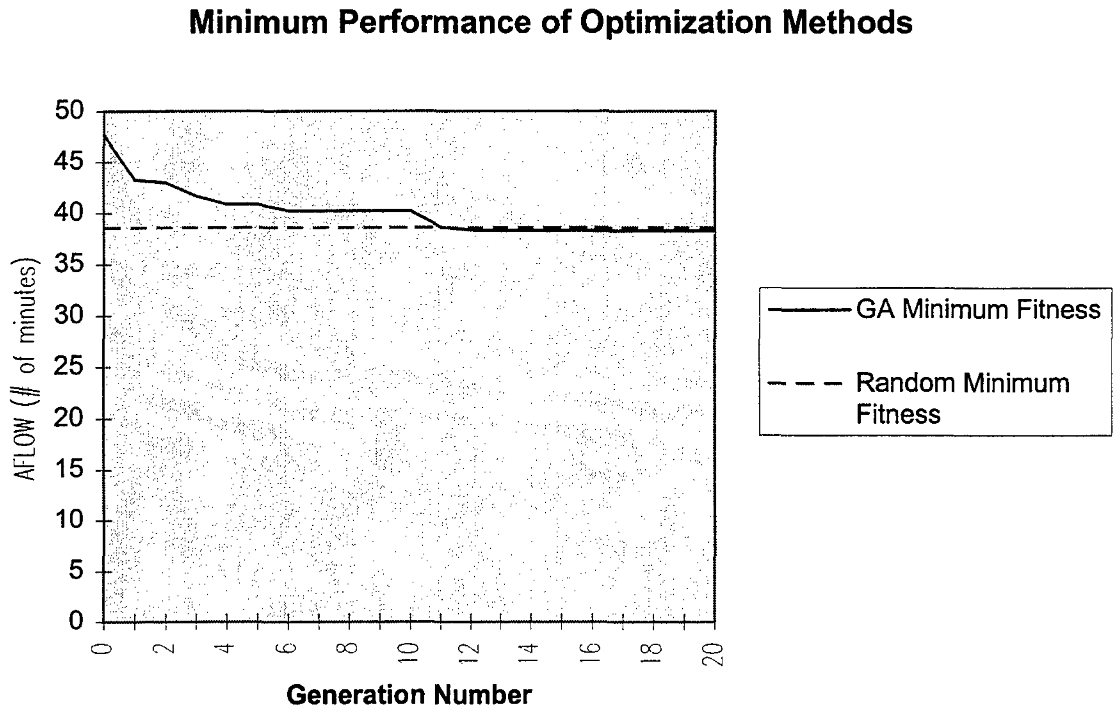


Chart 2.2: Minimum Performance



By comparing the intuitive search's results (Chart 2.1) with the minimum results of the random and GA searches (Chart 2.2), it becomes clear that the intuitive search was the least effective of the three methods. In fact, the intuitive search came far short of the lowest minimum times of the other two search methods (by over 100 minutes). By analyzing Chart 2.2, one may observe that the random search provided a least average time that was near the least time of the GA but slightly above it. Note, however, that the random search did not instantly reach this result (as it may seem in Chart 2.2). Its lowest average time was instead found over the same number of trials run by the GA. The random search's average performance, like the intuitive search, was far from the GA best average time. Of the three search methods used, the most effective was the GA. In the same amount of time taken by the random search, the GA provided a lower minimum time (by .3 minutes), as well as providing a better average performance.

The best minimum process time given by the GA assigned the cycle times found in Table 2.7 below:

Table 2.7: Best GA Performance

AFLOW (in minutes)	35.8
Machine 1 Cycle Time	7.6
Machine 2 Cycle Time	2.1
Machine 3 Cycle Time	3.12
Inspection Cycle Time	.59

Comparing Tables 2.6 and 2.7, it becomes clear that while Machine 2, Machine 3, and Inspection all went toward their minimum cycle times, Machine 1 went toward its maximum. It is hypothesized that this happened because when Machine 1 produces parts at a fast rate, the other machines cannot keep up with Machine 1's production. Machine 3 has an especially hard time keeping up because it uses labor to process parts, which limits it speed and processing power (how many parts can be processed at a time). This leads to parts getting stuck on conveyors as well as longer process times.

3.0 GA Performance on a Large Assembly Line Optimization Problem

The second system considered in the current effort focuses on a large assembly line problem. As shown in Diagram 3.1, this large system consisted of a "branching" line. It contained a startup machine (Machine 0), which pulled in a part to be worked on (again, referred to as a "widget"). From Machine 0, the part was sent by one of three conveyors (Conveyor 1, Conveyor 2, Conveyor 3) to one of three machines (Machine A1, Machine A2, Machine A3, respectively). Which machine the part was sent to was determined by a sequential order. Machine A2 was sent the first part, Machine A3 the second, Machine A1 the third, then Machine A2 and so on. These three machines rested on three parallel lines, so that parts could be in all three machines at the same time. From Machine A1, Machine A2, and Machine A3, the parts were sent by conveyors (Conveyor 4, Conveyor 5, Conveyor 6) to their next machine respectively (Machine B1, Machine B2, Machine B3). After being worked on there, the widgets were sent by conveyors (Conveyor 7, Conveyor 8, Conveyor 9, respectively) to a single inspection site (Inspection C). Here, one of every ten parts were routed to a "re-work station" (Machine E) by a conveyor (Conveyor 10). After being worked on here, the fixed parts were routed back to Inspection C by Conveyor 11 to be re-inspected and either sent back to be reworked or passed on. The parts that were eventually approved got sent to one of two machines (Machine D1, Machine D2) by conveyor (Conveyor 12, Conveyor 13 respectively). These machines worked on the parts and then sent them to Output to be shipped.

Diagram 3.1 shows the flow of parts from one machine to another, and Tables 3.1-3.4 show the settings for all members of this assembly line.

Table 3.1b: Machine Data – Variant

	Input	**Output**	**Actions on Finish**

Mach0	PULL from Widget out of World	If MOD(Qinput,3) = 1
		PUSH to Conv002 at Rear
		ElseIf MOD(Qinput,3) = 2
		PUSH to Conv003 at Rear
		ElseIf MOD(Qinput,3) = 0
		PUSH to Conv001 at Rear
		Else
		Wait
		Endif
			Qinput=Qinput+1

MachA1	Wait	PUSH to Conv004 at Rear	
MachA2	Wait	PUSH to Conv005 at Rear	
MachA3	Wait	PUSH to Conv006 at Rear	
MachB1	Wait	PUSH to Conv007 at Rear	
MachB2	Wait	PUSH to Conv008 at Rear	
MachB3	Wait	PUSH to Conv009 at Rear	

Inspect C	If NOCC(Conv011,1,2) < > 0
	PULL from Conv011 at Front
	ElseIf MOD(OutputA,3) = 0
	PULL from Conv007 at Front
	ElseIf MOD(OutputA,3) = 0
	PULL from Conv007 at Front
	ElseIf MOD(OutputA,3) = 0
	PULL from Conv007 at Front
	Else
	Wait
	Endif
		If MOD(OutputA,9) = 0
		PUSH to Conv010 at Rear
		ElseIf MOD(OutputA,2)=0
		PUSH to Conv012 at Rear
		ElseIf MOD(OutputA,2)=1
		PUSH to Conv013 at Rear
		Else
		Wait
		Endif
			OutputA=OutputA +1

MachD1	Wait	PUSH to SHIP	Output=Output+1
MachD2	Wait	PUSH to SHIP	Output=Output+1
MachE	Wait	PUSH to Conv011 at Rear	

Diagram 1: Assembly Line - Large Problem

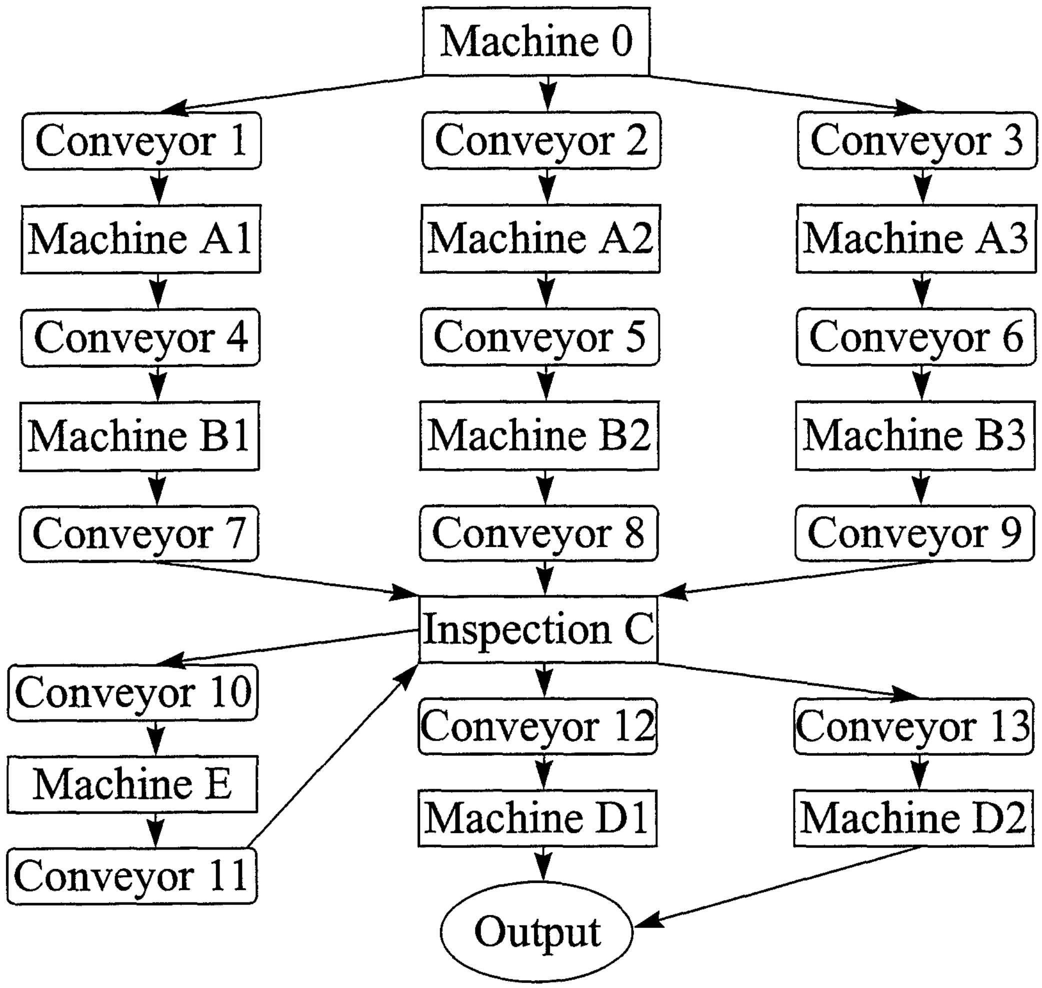


Table 3.1a: Machine Data - Common (for all machines)

Quantity	1
Priority	Lowest
Cycle Time	Variable
Type	Single
Reporting	Individual
Shift	N/A
Setup:	N/A
Breakdowns:	N/A

Table 3.2a: Conveyor Data - Common (for all conveyors)

Quantity	1
Priority	Lowest
Type	Queuing
Length	10
Maximum Capacity	10
Index Time	0.5
Input	Wait

Table 3.2b: Conveyor Data – Variant

Conveyor	**Output**
Conv 001	PUSH to MachA1
Conv 002	PUSH to MachA2
Conv 003	PUSH to MachA3
Conv 004	PUSH to MachB1
Conv 005	PUSH to MachB2
Conv 006	PUSH to MachB3
Conv 007	Wait
Conv 008	Wait
Conv 009	Wait
Conv 010	PUSH to MachE
Conv 011	Wait
Conv 012	PUSH to MachD1
Conv 013	PUSH to MachD2

Table 3.3: Variable Data

	Qinput	**OutputA**	**Output**
Quantity	1	1	1
Reporting	On	On	On
Type	Integer	Integer	Integer

Table 3.4: Part Data

	Widget
Group Number	1
Reporting	On

Any data areas in WITNESS that do not appear in these charts were empty or not available to the machines or conveyors to which they correspond.

Many of these parameters could potentially be adjusted by the GA. They include Quantity, Priority, Cycle Time, Length, Maximum Capacity, and Index Time. However, the only parameters that were adjusted with the GA were the Cycle Times of the Machines and the Inspection. In summary, the GA's task was to solve an eleven parameter optimization problem. This represents a dramatic increase in difficulty over the small optimization problem addressed in the previous report, which required only four parameters to be adjusted.

In order to run WITNESS simulations and collect data from them, the GA was placed within a Visual Basic "front end" program. This program starts up WITNESS and opens the simulation module to be tested. The GA then sends WITNESS the necessary data (all of the cycle times of the machines and inspection), and tells WITNESS to run a 500 minute simulation in batch. After the simulation is finished, the GA calls AFLOW, a WITNESS function that calculates the average amount of time a part spends on the assembly from start to finish. The objective of the GA in this research was to minimize AFLOW.

Before running the GA, each machine was provided with minimum and maximum cycle times (all in minutes).

Table 3.5: Cycle Time Ranges - Small Problem

Machine	Minimum	Maximum
Mach 0	1	8
Mach A1	2	7
Mach A2	3	9
Mach A3	2	8
Mach B1	1	8
Mach B2	2	7
Mach B3	3	9
Inspect C	0.5	5.2
Mach D1	2	7
Mach D2	3	9
Mach E	1	8

These parameters served as boundaries for the actual cycle times sent to WITNESS by the GA.

Once the GA sent WITNESS cycle times for the machines, it ran a simulation and collected the necessary data. It then repeated this process. Twenty simulations (one for each member of the GA population) were run. Once this generation was completed, the highest and lowest times calculated from AFLOW were written to a file, along with the generation number, average time, total time, and cycle times of the machines that had the lowest AFLOW value. Once this was done, a new generation of twenty members was formed, and the simulations were run again.

For the purposes of this research, three different methods of determining the lowest value of AFLOW were used. The first was the GA. The second was an "intuitive" method, by which all of the cycle times for all of the machines and inspection were set to their minimum values. Since all of the cycle times were set to their lowest respective values, a low value of AFLOW is "implied" by this method. The third method was a random selection. 400 sets of cycle times (the same total number used by the GA) were randomly generated and tested. Their best and average performances were calculated. Below are two charts of their performance. The first chart shows the average performance of the GA and the random search along with the "intuitive" result. The second chart shows only the minimum performance of the GA and the random search (since the intuitive answer proved to be drastically higher than the minimum random and GA answers).

Chart 3.1: Average Performance

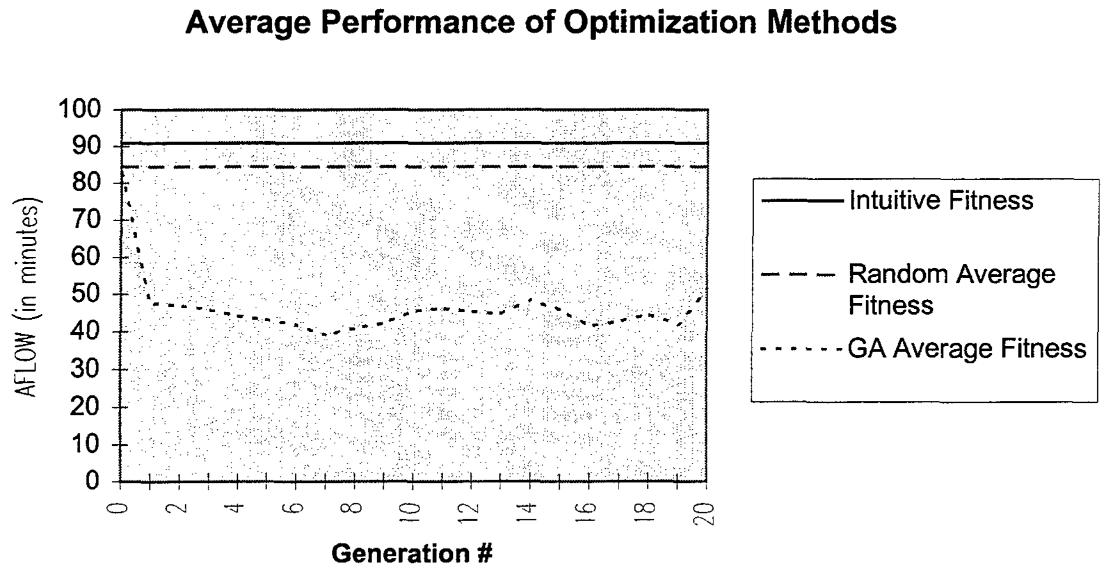
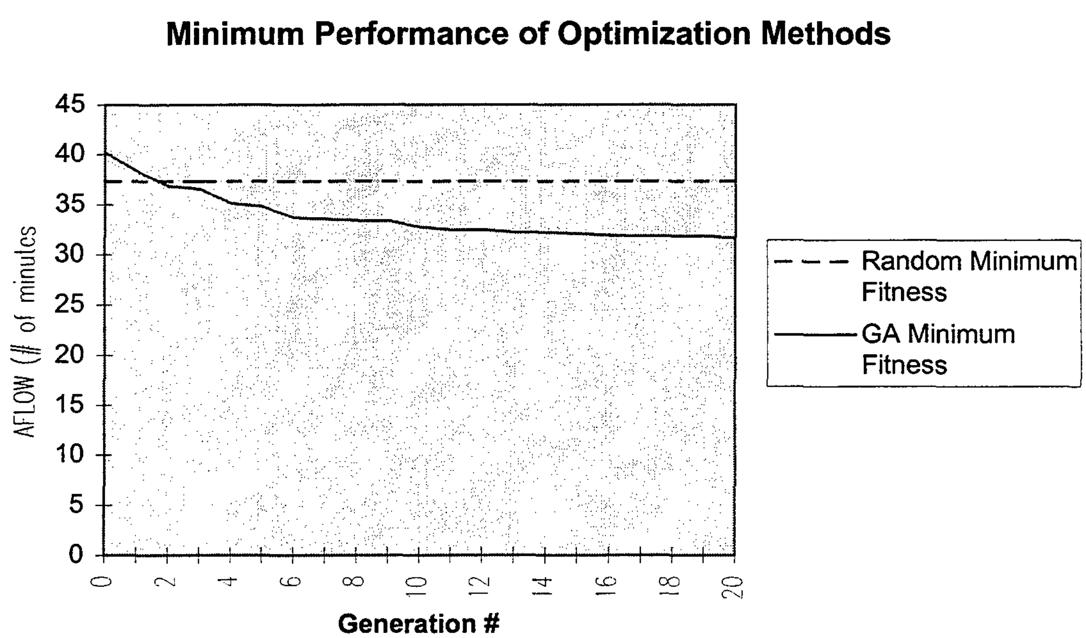


Chart 3.2: Minimum Performance



By comparing the results of the intuitive method (Chart 3.1) with the minimum results of the random and GA searches (Chart 3.2), it becomes clear that the intuitive

search was the least effective of the three methods. In fact, the intuitive search came far short of the lowest minimum times of the other two search methods (by 50-60 minutes). By analyzing Chart 3.2, one may observe that the random search provided a least average time that was near the least time of the GA but above it. Note, however, that the random search did not instantly reach this result (as it may seem in Chart 3.2). Its lowest average time was instead found over the same number of trials run by the GA. Its average performance, like the intuitive search, was far off the GA best average time. Of the three methods used, the most effective was the GA. In the same amount of time taken by the random search, the GA provided a lower minimum time (by 5 minutes), as well as providing a better average performance (by 40 minutes).

One of the minimum process times given by the GA had the following cycle times corresponding with it:

Table 3.6: Best GA Performance

AFLOW (in minutes)	32.85
Mach 0 Cycle Time	1.96
Mach A1 Cycle Time	2.08
Mach A2 Cycle Time	3.03
Mach A3 Cycle Time	2.84
Mach B1 Cycle Time	1.22
Mach B2 Cycle Time	2.49
Mach B3 Cycle Time	3.55
Inspect C Cycle Time	.83
Mach D1 Cycle Time	2.24
Mach D2 Cycle Time	3.18
Mach E Cycle Time	5.15

Comparing Tables 3.5 and 3.6, it becomes clear that most of the machines went towards their minimum cycle time. This may be explained by examining the "intuitive" search results. In general, when all machines are sent to their minimum cycle times, the "A" machines process parts faster than the "B" machines. At the same time, the "B" machines produce parts faster than the Inspector can process them. By holding the process times of the "A" machines closer to the "B" machines, parts tend to not get so backed up on the conveyors, which lowers each part's average process time in the assembly line.

4.0 Conclusions and Future Work

From this work, it is clear that the GA is potentially an effective search method for optimizing the parameters associated with a manufacturing line. In both lines studied, the GA outperformed both an intuitive approach and a random search routine.

There are still a number of questions to be answered. These questions include:

- Is there another search method (such as a derivative search) that is more effective than the GA?
- If the GA is run for more generations, is a better solution obtained?
- How well will the GA optimization approach work when the size and complexity of the lines are increased?
- Will the GA optimization approach be able to effectively handle multiple optimization objectives?

These questions and others will be addressed in the second phase of this effort.

Table 4.1 SubModel Element Information

Sub-Model	Buffers	MainProcess Element	Parts	Quality Distribution	Misc. Variables	Ship Variable	Scrap Variable	Labor	Attributes
manprep1 2-1	MandBuff MandRec	ManPrep1 (Batch)	Mandrel PrepMand	QualMP1	Liner NewMand		ScrapMP	Gen Maint	Group-1
filwind1 3-1	FW1Buff	FilWind1 (Batch)	Mandrel PrepMand FWPart	QualFW1	Solv1add Solv1use Solv2add Solv2use		ScrapFW	Gen Maint	Group-1
cure1 4-1		Cure1 (Conveyor)	CurePart	QualC1		ShipC	ScrapC ScrapC1	Gen Maint	Group-1
cure2 4-2		Cure2 (Wait Buffer) Cure2M (Single)	CurePart	QualC2		ShipC	ScrapC ScrapC2	Gen Maint	Group-1
cure3 4-3	C3Buff	Cure3 (Batch)	CurePart	QualC3		ShipC	ScrapC ScrapC3	Gen Maint	Group-1
cure4 4-4	C4Buff BagRec	Cure4 (General)	CurePart Bags	QualC4	NewBags	ShipC	ScrapC ScrapC4	Gen Maint	Group-1 Group-2
manrem1 5-1	MRBuff	ManRem1 (Production)	MRParts Mandrel	QualMR	MRUses MRManUse	ShipMR	ScrapMR	Gen Maint	Group-1
mach1 6-1	MachBuff	Mach1 (Single)	MachPart	QualMach		ShipMa	ScrapMa ScrapF,F0,F1F2,F3,F4,F5	Gen Maint	Group-1
assem1 6-2	AsBuff	Assem1 (Single)	AsPart	QualA		ShipAs	ScrapA ScrapF,F0,F1 F2,F3,F4,F5	Gen Maint	Group-1
cut1 6-3	CutBuff	Cut1 (General)	CutPart	QualC	CutMP CutFW CutMR CutMach CutAssem CutCure	ShipCut	ScrapCut ScrapF,F0,F1 F2,F3,F4,F5	Gen Maint	Group-1
qibatch 7-1	QBBuff	QIBatch (General)	InspPart	QualQIB	QBatch	ShipQ	ScrapQB	Gen Maint	Group-1
qiind 7-2	QIBuff	QIInd (Single)	InspPart	QualQII		ShipQ	ScrapQI	Gen Maint	Group-1

Group1 Attributes - Assem, Cure, Cut, FW, Machine, ManUses, MandRem, Mandprep, QIB, QII, Quality, Uses
Group 2 Attributes - BagUses, UsesB

APPENDIX J

Using the DTAME System User Interface

How the Interface Works.

The interface was developed using Microsoft Visual Basic® on a PC compatible platform. Using the interface tools available in this environment a series of input screens were developed that allow the user to easily enter specific parameter values. These screens can be classified as preliminary question screens and detailed information screens. The function of the preliminary question screens is to determine the initial configuration of the simulation model. The user is asked to first determine type of manufacturing problem that will be analyzed. Currently the system is designed to handle a generalized filament winding product or the more specific VARTM products that utilize lay-up processes. Figure 1 shows the initial manufacturing type selection screen.

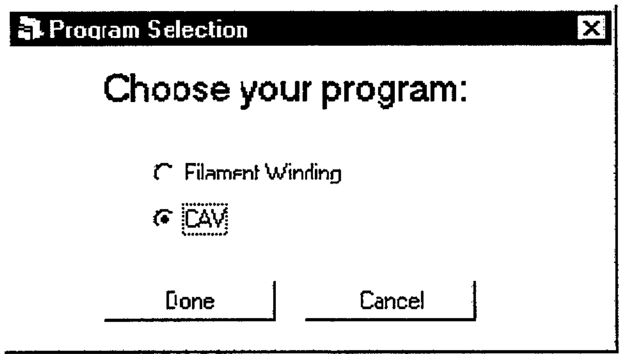


Figure 1. Initial Process Selection

After the manufacturing type is selected the user is queried for information that generally defines the manufacturing environment. This information is used to develop the available resources for the simulation environment as well as determine the specific manufacturing configuration. Figure 2 shows an example of the general process information interface screens. In this example the exact number and types of lay-ups are determined. This will in turn directly determine the line layout for the VARTM lay-up process.

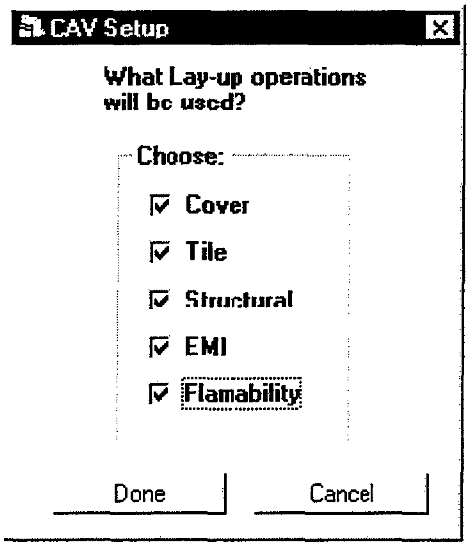


Figure 2. Lay-up Operation Selection

Figure 3 shows another example of the general parameter interface. In this example, the labor and specific tooling for the facility are defined. These parameters will represent general resources in the simulation environment.

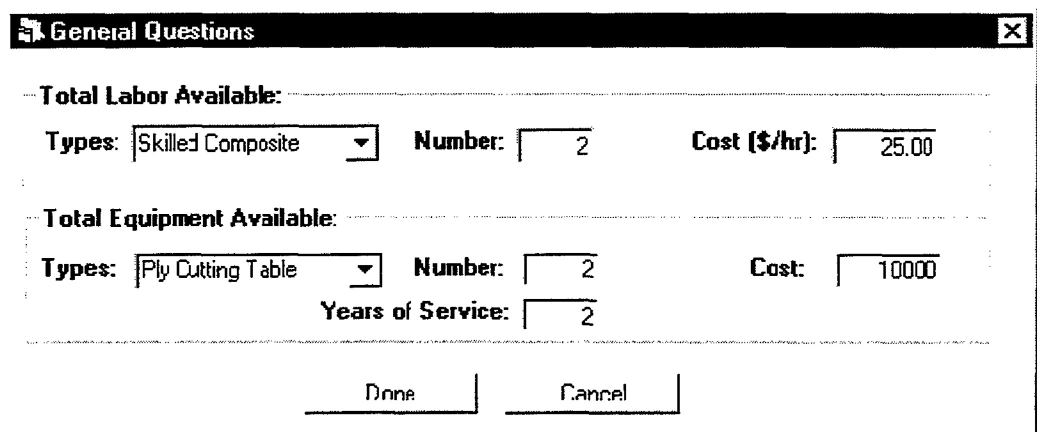


Figure 3. General Operations

Once the general input screens are complete, the process flow diagram for the selected manufacturing scenario is constructed and displayed. Figure 4 shows a manufacturing configuration that requires various set-up, lay-up, and curing procedures. The process definitions are grouped and color-coded by type to assist the user in easy identification.

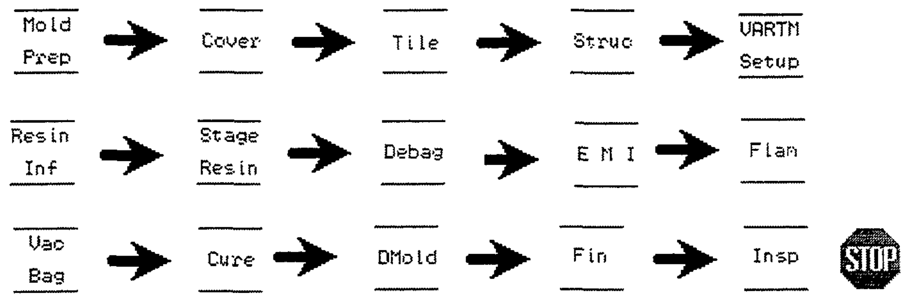


Figure 4. Initial Layout Based on Lay-up Selections

Each of the icons is linked to its own edit screen. This information represents the specific operating parameters for the manufacturing station. While much of the information that is required by the system is common to all manufacturing stations, these screens are tailored to the individual manufacturing station's requirements. Figure 5 shows an example of a typical input screen for a manufacturing station. The input screen is divided into a set of tabbed areas. Each tabbed area requests information regarding a different aspect of the manufacturing station. These areas include Set-up, Normal Operation, Breakdowns, Scheduled Maintenance, Cleaning, and Materials.

The user is required to complete the input screen for each of the manufacturing stations before a simulation or static analysis can be conducted. The individual station information can be entered randomly and does not necessarily need to totally complete. Only the information that is required by the specific model must be input. For example, if the user plans to only perform a static analysis on the model then only the cycle time, down time and repair time information must be present. However, a simulation run would require much more information and the user may not know exactly which parameters are required. Therefore, it is a good practice to populate the model definition as completely as possible, even if all the information may not be needed at the present time.

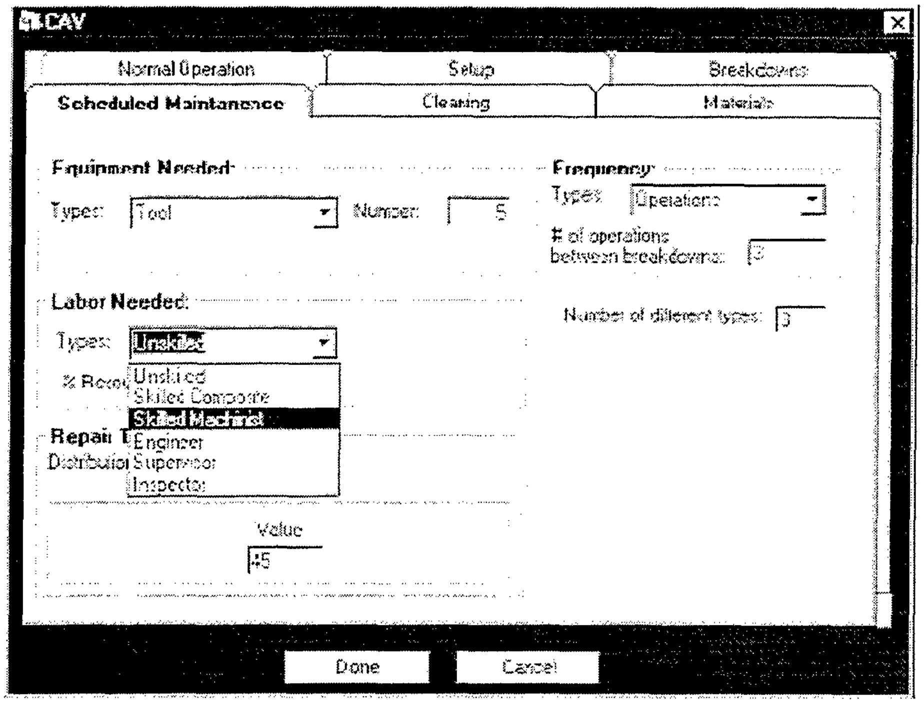


Figure 5. Typical Input Screen for Simulation Element

The information can be saved and retrieved from data files. This means that the model can be reused as often as desired. This is accomplished by using the "Save" and "Open" commands located in the "File" menu. These commands activate the windows common file control dialog that requests the user to specify the pathname of the data file. The user can either type the file pathname or use the standard browse option to locate an exiting file or the appropriate sub-directory. Once selected the file is opened and the model either saved or reloaded into memory.

This save and load capability gives the user the ability to make analyses on slight variations in the model. A baseline model can be created, analyzed, and saved. Then, the model can be altered, analyzed, and saved under a new identity. The results of the individual models can then be examined to compare how the parameter variations effect the performance of the models.

Simulations and static analyses are conducted on the model by selecting the appropriate item from the "Analyze" menu. For a simulation, the simulation software package is initiated and the individual model station parameters are passed to it. Once the model is populated in the simulation software, the simulation is run. The simulation results are then displayed in the interface for the user.

The static analysis routines are located within the interface itself. Therefore, no communications with external software is required. This analysis only requires the cycle time, down time, and repair time parameters for each of the stations. The information is processed and the results presented.

As previously stated the purpose of the user interface is to provide an easy to use method for the information required by the various components of the DTAME system to be input by the user. When ever possible, multiple choice selection boxes, check boxes, and other means of simple data display are utilized. The reusability of the information, cross software independence, and centralized analysis results make this interface a valuable addition to the DTAME system.